Downscaled CMIP3 and CMIP5 Climate Projections

Release of Downscaled CMIP5 Climate Projections, Comparison with Preceding Information, and Summary of User Needs

Bureau of Reclamation

Climate Analytics Group

Climate Central

Lawrence Livermore National Laboratory

Santa Clara University

Scripps Institution of Oceanography

U.S. Army Corps of Engineers

U.S. Geological Survey

May 2013

Downscaled CMIP3 and CMIP5 Climate Projections

Release of Downscaled CMIP5 Climate Projections, Comparison with Preceding Information, and Summary of User Needs

7 May 2013

Authored by:

Levi Brekke, Bureau of Reclamation
Bridget L. Thrasher, Climate Analytics Group
Edwin P. Maurer, Santa Clara University
Tom Pruitt, Bureau of Reclamation

Review and Contributions from:

Jeff Arnold, U.S. Army Corps of Engineers
Dan Cayan, Scripps Institution of Oceanography, University of California San Diego and U.S. Geological Survey
Tapash Das, CH2M-Hill
Michael Dettinger, U.S. Geological Survey
Phil Duffy, Lawrence Livermore National Laboratory
Subhrendu Gangopadhyay, Bureau of Reclamation
Ken Nowak, Bureau of Reclamation
James Prairie, Bureau of Reclamation
Claudia Tebaldi, Climate Central
Adam Terando, U.S. Geological Survey
Seshu Vaddey, Bureau of Reclamation

Prepared for:

Users of the "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections: Release of Downscaled CMIP5 Climate Projections" website at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/.

Abbreviations and Acronyms

BC	bias-correction
BCCA	Bias-Correction Constructed Analogues
BCCA3	BCCA CMIP3
BCCA5	BCCA CMIP5
BCSD	Bias-Correction Spatial Disaggregation
BCSD3	BCSD CMIP3
BCSD5	BCSD CMIP5
CMIP	Coupled Model Intercomparison Project
CMIP3	Coupled Model Intercomparison Project phase 3
CMIP5	Coupled Model Intercomparison Project phase 5
Collaborators	Bureau of Reclamation, Climate Analytics Group, Climate Central, Lawrence Livermore National Laboratory, Santa Clara University, Scripps Institution of Oceanography, U.S. Army Corps of Engineers, and the U.S. Geological Survey
CPO	Climate Programs Office
CSC	U.S. Department of the Interior Climate Science Centers
DTR	diurnal temperature range
ENSO	El Niño Southern Oscillation
ESRL	Earth System Research Laboratory
GDP	Geo Data Portal
ghg	greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
km	kilometer
MAGICC	Model for the Assessment of Greenhouse-gas Induced Climate Change
MAPP	Modeling Applications, Prediction and Projections
mm/day	millimeters per day
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research

Abbreviations and Acronyms

NCL	NCAR Command Language
NEX	NASA Earth Exchange
NOAA	National Oceanic and Atmospheric Administration
NW CSC	U.S. Department of the Interior Northwest Climate Science Center
º	degrees
ºC	degrees Celsius
PI	Principal Investigator
RCP	representative concentration pathways
Reclamation	Bureau of Reclamation
RISA	Regional Integrated Science and Assessment
SRES	Special Report on Emissions Scenarios
SST	sea surface temperatures
UCLA	University of California, Los Angeles
WCRP	World Climate Research Programme

Acknowledgments

Support provided by:

Bureau of Reclamation Science and Technology Program
Bureau of Reclamation WaterSMART Basin Studies Program
U.S. Army Corps of Engineers Responses to Climate Change and Actions for Change Programs
Lawrence Livermore National Laboratory – Green Data Oasis

Acknowledgements and Citation of these Projections

When publishing research based on projections from this archive, please include two acknowledgements:

1. Acknowledge the superseding effort:

    a. For Coupled Model Intercomparison Project phase 3 (CMIP3), the following is language suggested by the CMIP3 archive hosts at the Program for Climate Model Diagnosis and Intercomparison (PCMDI):

    "We acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI), and the World Climate Research Programme (WCRP) Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, U.S. Department of Energy."

    PCMDI also requests that in first making reference to the projections from this archive, please first reference the CMIP3 dataset by including the phrase "the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset." Subsequent references within the same publication might refer to the CMIP3 data with terms such as "CMIP3 data," "the CMIP3 multi-model dataset," "the CMIP3 archive," or the "CMIP3 dataset."

    b. For Coupled Model Intercomparison Project phase 5 (CMIP5), the model output should be referred to as "the CMIP5 multi-model ensemble [archive/output/results/of simulations/dataset/ ...]." In publications, you should include a table (referred to below as Table XX) listing the models and institutions that provided model output used in your study. In this table, and as appropriate in figure legends, you should use the CMIP5 "official" model names found in "CMIP5 Modeling Groups and their Terms of Use" (http://cmip-pcmdi.llnl.gov/cmip5/docs/CMIP5_modeling_groups.pdf). In addition, an acknowledgment similar to the following should be included in your publication:

"We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups (listed in Table XX of this paper) for producing and making available their model output. For CMIP, the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals."

where "Table XX" of your paper should list the models and modeling groups that provided the data you used. In addition, it may be appropriate to cite one or more of the CMIP5 experiment design articles listed on the CMIP5 reference page.

2. Second, generally acknowledge this archive as "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections" archive at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections. To reference specific information in the archive, you also use the following references:

   a. For Bias-Correction Spatial Disaggregation (BCSD) CMIP3 climate projections: Maurer, E.P., L. Brekke, T. Pruitt, and P.B. Duffy, 2007, "Fine-resolution climate projections enhance regional climate change impact studies," *Eos Trans. AGU*, 88(47), 504.

   b. For Bias-Correction Constructed Analogues (BCCA) CMIP3 climate projections: Maurer, E.P., H.G. Hidalgo, T. Das, M.D. Dettinger, and D.R. Cayan, 2010, "The utility of daily large-scale climate data in the assessment of climate change impacts on daily streamflow in California," *Hydrology and Earth System Sciences*, 14, 1125-1138, doi:10.5194/hess-14-1125-2010.

   c. For BCSD CMIP3 hydrologic projections: Reclamation, 2011, *West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Surface Water Projections*, Technical Memorandum No. 86-68210-2011-01, prepared by the U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Denver, Colorado, 138 p.

   d. For BCSD and BCCA CMIP5 climate: Provide citation to: Reclamation, 2013. *Downscaled CMIP3 and CMIP5 Climate Projections: Release of Downscaled CMIP5 Climate Projections, Comparison with Preceding Information, and Summary of User Needs.*

U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Denver, Colorado, 116 p., available at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/downscaled_climate.pdf.

Executive Summary

The World Climate Research Programme (WCRP) develops global climate projections through its Coupled Model Intercomparison Project (CMIP) roughly every 5 to 7 years. These projections have informed Intergovernmental Panel on Climate Change Assessment Reports, as well as various research, assessment, and educational activities related to climate change processes and outcomes, mitigation, and adaptation. Such activities have primarily been served by CMIP phase 3 (CMIP3) results since 2007. During 2012-2013, WCRP released global climate projections from CMIP phase 5 (CMIP5). Given the arrival of CMIP5 and how it differs from CMIP3, users are expected to show interest in understanding what this new information means for local impacts assessment and adaptation planning. This motivates development of downscaled CMIP5 climate projections to enable users to compare this new information with the preceding downscaled CMIP3 information.

Two statistical downscaling techniques – monthly bias-correction and spatial disaggregation (BCSD) and daily bias-correction and constructed analogs (BCCA) – have been applied to a large ensemble of new climate projections released through the WCRP CMIP5. These downscaled CMIP5 climate projections are now available through the "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections" website (DCHP website) at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/. The DCHP website is an update to the "Bias Corrected and Downscaled WCRP CMIP3 Climate and Hydrology Projections" website.

This memorandum accompanies the first of two DCHP website updates scheduled for 2013. The second update will be hydrology projections derived from the monthly BCSD CMIP5 climate projections; the update is expected in summer 2013. The memorandum summarizes the motivation and context for the website updates; discusses changes included in the website update, including data development methods; provides cursory comparison of new and old downscaled information; summarizes user needs in understanding these differences; and concludes with a brief description of ongoing research activities addressing these differences.

Motivation and Context (Section 1)

The DCHP website is a collaborative effort that began in 2007 and today is supported by the Bureau of Reclamation (Reclamation), Climate Analytics Group, Climate Central, Lawrence Livermore National Laboratory, Santa Clara University, Scripps Institution of Oceanography, U.S. Army Corps of Engineers, and the U.S. Geological Survey (Collaborators). Collaborators began the effort with a focus on developing and serving monthly BCSD climate projections. Responding to user needs, the service scope expanded to include daily BCCA CMIP3 climate over the contiguous U.S. and BCSD CMIP3 hydrology over the western U.S. (2011). Through these content additions, scoping has been steered by recognition that water managers need to assess what future climate change could mean for the management of their systems, as well as when climate change vulnerabilities and impacts would appear to cross thresholds, triggering the need for adaptive intervention. In order to assess such needs, managers must be able to quickly and easily access global climate projection information that has been bias-corrected to account for systematic climate model errors and downscaled to scales of local impacts.

Anticipating the release of CMIP5, downscaling activities began under the direction of Climate Analytics Group, Climate Central, and Santa Clara University, through support from Reclamation, U.S. Army Corps of Engineers, Lawrence Livermore National Laboratory, and National Aeronautics and Space Administration (NASA) Ames Research Center. Activities focused on applying the monthly BCSD and daily BCCA methods in order to develop outputs suitable for comparing the downscaled CMIP5 and CMIP3 modeled outputs.

About the Downscaled Climate Projections (Section 2)

The website serves downscaled CMIP3 and CMIP5 climate information that both feature large ensembles of simulated: (a) monthly projections of total precipitation and monthly-mean daily average temperature; and (b) daily projections of the precipitation, daily minimum temperature, and daily maximum temperature. The downscaled CMIP5 products also include monthly projections of monthly-mean daily-minimum and daily-maximum temperature, as well as daily projections of daily-average temperature. Both the CMIP3 and CMIP5 information resources represent large collections of global climate models and a representative range of the greenhouse gas emissions scenarios featured in CMIP3 and CMIP5.

The monthly BCSD and daily BCCA downscaling methods were consistently applied to CMIP5 and CMIP3 where possible, with several exceptions in the CMIP5 application involving methods refined in the time since the CMIP3 application. Quality assurance measures were implemented prior to production to ensure downscaling code reproducibility, during production to verify quality of global climate projection input data and downscaling output data files, and after production to verify that results were developed without dependence on computing environment.

May 7, 2013, Release Notes

Moving forward, it is expected that this memorandum will serve as a living document describing the Collaborators' information resources and DCHP website content pertaining to downscaled climate projections. At the time of this website update, several notes apply to the release, interpretation, and use of the downscaled CMIP5 climate information:

- The CMIP5 projections represent a new opportunity to improve our understanding of climate science, which is evolving at a rapid pace. As new information such as CMIP5 is developed, the DCHP website collaborators are taking active roles in evaluating and incorporating it, as appropriate, into ongoing activities.

- While CMIP5 projections may inform future analyses, many completed and ongoing studies remain informed by CMIP3 projections that were selected as best information available at the time of study. Even though CMIP5 is newer, it has not been determined to be a better or more reliable source of climate projections compared to existing CMIP3 climate projections. CMIP5 projections should be considered an addition to (not a replacement of) the existing CMIP3 projections unless the climate science community can offer an explanation as to why CMIP5 should be favored over CMIP3.

- Because the CMIP5 model solutions have been available to the wider community only very recently, understanding how and why CMIP5 results differ from those in CMIP3 is at the early stage. It is thought now that any differences broadly relate to updates and other differences in the climate models used for CMIP5 and to the new set of climate forcing emissions scenarios. However, understanding those differences and their effects on regional specific is still underway.

- Section 3 provides a cursory summary of differences between downscaled CMIP5 and CMIP3 climate projections over the conterminous U.S. Most of the differences arise from differences in the CMIP5 global climate model projections of regional scale temperature and precipitation. However, some of these differences are due to the downscaling technique, meaning that the differences in downscaled information are similar to, but not precisely the same as, differences in global CMIP5 and CMIP3 climate information over the U.S. prior to downscaling.

- Collaborators are releasing the CMIP5 content additions at the DCHP website with the goal of accelerating community understanding of the CMIP5 versus CMIP3 differences depicted here and promoting use of an ever more complete representation of possible future climates. Releasing the new information to the large user community will build shared awareness of CMIP5 versus CMIP3 similarities and differences, as well as enhance the encouragement of the large community of users already familiar with CMIP3 to evaluate, explore, and diagnose the projections.

Comparing BCSD CMIP5 Versus CMIP3 Information (Section 3)

This memorandum offers a cursory comparison of downscaled CMIP5 and CMIP3 climate projections. The purpose is to orient users on the more noticeable similarities and differences over various regions of the contiguous U.S. Characterization of more localized differences is an activity left to the reader, aided by using the DCHP website's functionality, which enables the request of data-subsets by variable, projections, geographic area, and time period. The comparison focuses on monthly BCSD results because: (1) most website data requests involve this resource, and (2) prior studies have shown that at monthly to coarser time resolution, downscaling results have been similar, whether they were derived using monthly BCSD or daily BCCA.

A comparison of downscaled CMIP5 and CMIP3 climate projections over the western U.S. shows broad regional similarities (e.g., similar levels of warming throughout much of the West and similar precipitation trends towards the North and Southwest). There are also notable differences in some regions (e.g., greater warming over the Upper Columbia Basin, less precipitation over the northern Great Plains, and more precipitation over California and the Upper Colorado Basin from CMIP5 compared to CMIP3). Projections showing wetter portions of California and the Upper Colorado Basin are notable because they challenge previous projections from CMIP3 that suggested these regions will become drier, resulting in reduced runoff. It is important to recognize that, while CMIP5 offers new information, more work is required to better understand CMIP5 and its differences from CMIP3, including:

1. Understanding why CMIP5 projected changes in annual climate differ from those in CMIP3, and the extents to which these differences are attributable to changes in global climate model composition and/or use of different climate forcing scenarios.

2. Understanding how the differences between downscaled CMIP5 and CMIP3 projections are sensitive to the choice of emissions scenario.

3. Understanding why CMIP5 projected changes in monthly climate differ from those in CMIP3, and how climate model simulation of season-specific mechanisms contributes to these differences.

4. Understanding why the quantile-mapping bias-correction scheme used in BCSD and BCCA resulted in wetter results in the CMIP5 application compared to the CMIP3 application, with potentially greater effect when starting from relatively wet REGRID[1] changes (e.g., as found for the Upper Colorado Basin).

5. Understanding the respective roles of BCSD's quantile-mapping bias-correction technique and spatial disaggregation downscaling technique in modulating the intensity and spatial pattern of annual climate change from REGRID to BCSD projections.

Improving our Understanding of Downscaled CMIP5 Information (Section 4)

The cursory comparison of BCSD CMIP5 and CMIP3 information addresses differences in projected annual to monthly climate variables and for a limited set of scales and statistics. The needs arising from this evaluation fit within a broader outline of potential user interests surrounding the release of downscaled CMIP5 climate projections, which are not addressed in this memo or the data it describes. These interests include:

- **Characterizing the differences:** What are the differences among CMIP5 and CMIP3 portrayals of different hydroclimate variables (e.g., precipitation, temperature, runoff, evapotranspiration, etc.) at different space scales (e.g., hydrologic unit code 2-digit to 12-digit) and time scales (e.g., daily, seasonal, annual, multi-year)?

- **Explaining the differences:** How are these differences attributable to the use of new global climate models, use of new climate forcing scenarios, chosen downscaling technique, and chosen hydrologic analysis methodology (for applicable variables)?

- **Relating to past decision support:** How sensitive are the results from CMIP3-informed studies to these differences? What does this mean for decisions supported by those studies?

[1] REGRID refers to the uncorrected global climate projection results that have been translated (or regridded) from the native spatial resolutions of disparate climate models to a common spatial resolution. REGRID precedes the two steps of BCSD: bias-correction at the coarser REGRID resolution (resulting in BC projections) and spatial disaggregation to the finer downscaled resolution (resulting in BCSD projections).

- **Relating to future decision support:** Which dataset should be used: (1) CMIP3 until CMIP5 is further evaluated and understood? (2) CMIP5 because it features the latest advancements in climate modeling and estimation of future climate forcing? (3) pooled CMIP3 and CMIP5 unless rationale can be offered as to why one is more credible than the other? What CMIP5 information is reliable enough to support adaptation investments, and for what kinds of investment situations?

Various Federal agencies and programs are currently funding research to help develop understanding in these areas, including the National Oceanic and Atmospheric Administration (NOAA) Climate Programs Office (CPO) Modeling, Applications, Predictions, and Projections program through its CMIP5 Task Force; the NOAA CPO Climate and Societal Interactions - Regional Integrated Sciences and Assessments (RISA) program; and the U.S. Department of the Interior through its network of regional Climate Science Centers.

Table of Contents

Page

Tables

Page

Figures

Page

Figures (continued)

Page

1. Introduction

This memorandum describes new downscaled climate projections developed over the contiguous U.S. and how they compare to the preceding generation of downscaled projections. The new climate projections have been made available through the "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections" website (DCHP website),[1] which is an update to the predecessor website , "Bias Corrected and Downscaled WCRP CMIP3 Climate and Hydrology Projections."

This DCHP website update, featuring new downscaled climate projections and data subset-request features, is the first of two website updates scheduled for 2013. The second update will feature the release of hydrology projections corresponding to the new downscaled climate projections and is expected to occur during summer 2013.

This memorandum summarizes data development methods, provides cursory comparison of new and old downscaled information, summarizes user needs for understanding these differences, and provides a brief description of ongoing research activities addressing these differences. The remainder of this introduction provides context for the development of this new information resource.

1.1 New Global Climate Projections through CMIP5

The World Climate Research Program (WCRP) develops global climate projections through its Coupled Model Inter-comparison Project (CMIP) roughly every 5 to 7 years. CMIP results inform the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports. For example, the projections from CMIP phase 3 (CMIP3) (Meehl et al., 2007) informed the IPCC Fourth Assessment, released in 2007, and have since been used to support many assessment, research, and educational activities concerned with climate change mitigation and adaptation.

During 2012-2013, WCRP released global climate projections from CMIP phase 5 (CMIP5)[2] (Taylor et al., 2011), which will inform the IPCC Fifth Assessment (expected in 2014). The projections were generated using a set of new global climate models (Knutti and Sedláček, 2012) that collectively reflect varying degrees of advancement in climate science and modeling since CMIP3.

[1] http://gdo-dcp.ucllnl.org/downscaled_cmip_projections.

[2] For WCRP information, see http://www.wcrp-climate.org/. For CMIP5 information, see http://cmip-pcmdi.llnl.gov/cmip5/.

CMIP5 climate projections were also developed using a new set of climate forcing scenarios (i.e., representative concentration pathways [RCP] [van Vuuren et al., 2011]) that reflect recent advancements in integrated assessment modeling to characterize future developments in global greenhouse gas (GHG) emissions since release of the predecessor scenarios, known as the Special Report on Emissions Scenarios (SRES) scenarios (IPCC, 2000).

Given the arrival of CMIP5 and how it differs from CMIP3, users are expected to show interest in understanding what this new information means for local impacts assessment and adaptation planning, which motivates development of downscaled translations of CMIP5. Users may also be interested in understanding how the new information compares to CMIP3 information that has been informing their efforts since 2007. As with CMIP3, the CMIP5 climate projections express future climate uncertainty stemming from choice in climate forcing emissions scenario, climate model structure, and internal variation (Hawkins and Sutton, 2009; 2010), with some research suggesting that internal variation is a large source of uncertainty in the temperature and precipitation projections at regional to local scales (Deser et al., 2010). In addition to that, the downscaled projections accumulate uncertainty from choices in how to bias-correct and spatially downscale climate projections.

1.2 Downscaling Motive and Past Application to CMIP3

The DCHP website is a collaborative development effort that began in 2007 and today is supported by the Bureau of Reclamation, Climate Analytics Group, Climate Central, Lawrence Livermore National Laboratory, Santa Clara University, Scripps Institution of Oceanography, U.S. Army Corps of Engineers, and the U.S. Geological Survey (Collaborators). Collaborators began the effort with a focus on developing and serving monthly bias-correction and spatial disaggregation (BCSD) climate projections in 2007. Responding to user needs, the service scope expanded to include daily bias-correction and constructed analogs (BCCA) CMIP3 climate over the contiguous U.S. and BCSD CMIP3 hydrology over the Western U.S. (2011).[3] Through these content additions, scoping has been steered from recognition that water managers need to assess what future climate change could mean for the management of their systems, and to assess when climate change vulnerabilities and impacts would appear to cross

[3] BCSD CMIP3 hydrology projections over the Western U.S. are not discussed in this memorandum. To learn more about them, visit: http://www.usbr.gov/WaterSMART/docs/west-wide-climate-risk-assessments.pdf. This memorandum will be edited to describe hydrologic projections development once BCSD CMIP5 hydrology projections over the contiguous U.S. are completed (expected in summer 2013).

thresholds triggering the need for adaptive intervention. In order to assess such needs, managers must be able to quickly and easily access global climate projection information that has been bias-corrected to account for systematic climate model errors and downscaled to reflect local climatological features.

The need for developing downscaled climate projections arises because the scale of global climate modeling is still too coarse to support local impacts assessment for many types of resources (e.g., hydrology in complex terrain, aquatic ecosystems, managed water resources, and other managed natural resource systems). This was found to be the case with CMIP3 and is still the case with CMIP5 as global climate projections have a horizontal resolution that is generally 100 kilometers (km) or greater. For CMIP3, many downscaling efforts emerged, featuring different techniques (dynamical to statistical [Fowler et al., 2007]) and targeted spatial resolutions (e.g., 1/8 degree (º), 1/16º, and finer resolutions).

This memorandum highlights CMIP5 downscaling that builds on a CMIP3-related effort (Maurer et al., 2007), originally based on application of a statistical technique: monthly BCSD (Wood et al., 2002; 2004, appendix A). The initial effort was led by Reclamation, Santa Clara University, and Lawrence Livermore National Laboratory and shaped by the following goals:

1. Develop a downscaled information resource that represents many of the available global climate projections in order to promote exploration of local climate projection uncertainty and risk-based planning,

2. Feature a method that has been well established in impacts literature.

3. Apply the method on a time domain that can flexibly support impacts assessment and planning for different future time periods.

4. Apply the method in a spatially consistent fashion throughout the contiguous U.S. and its transboundary watersheds in order to set up use of a common information resource by a broad and diverse user base.

5. Apply the method at a resolution fine enough to support a variety of impacts applications, while also respecting the limits of gridded historical weather observations that are necessary to guide the technique’s application.

Monthly BCSD was selected to support the effort because it could be applied in a way that reasonably satisfied all of these goals. This led to the development of a 112-member ensemble of monthly BCSD CMIP3 temperature and precipitation projections representing 16 CMIP3 climate models and 3 of the SRES GHG scenarios featured in CMIP3 (IPCC, 2000). Each downscaled projection was developed at 1/8º resolution over a geographic domain encompassing the contiguous U.S. and transboundary watersheds, and for a time domain of 1950-2099. Since their release, more than 1,000 users have accessed this information through the predecessor website ("Bias Corrected and Downscaled WCRP CMIP3 Climate and Hydrology Projections") and have requested information subsets by variable, projection, geographic domain, and time period for use in a variety of research, planning, and educational activities.

In 2009, users indicated interest in having access to daily downscaled climate projections reflecting the daily weather patterns simulated in global climate simulations. It was recognized that such information might benefit impacts studies focused on submonthly climate phenomena, including flood impacts studies concerned about changes in daily precipitation patterns and ecosystem impacts studies framed by future assumptions on diurnal temperature range. To satisfy this interest, the number of entities involved in archive development broadened to include additional members from the current list Collaborators (Climate Central, Scripps Institution of Oceanography, U.S. Army Corps of Engineers, and U.S. Geological Survey). These new members contributed to an effort to downscale a large collection of CMIP3 climate projections using daily BCCA (Hidalgo et al., 2008; Maurer et al., 2010, appendix A). These daily BCCA CMIP3 climate projections were added to the archive in 2011, along with additional information resource describing Western U.S. hydrology associated with the monthly BCSD CMIP3 projections.[4] Compared to the monthly BCSD application, the daily BCCA application was conducted with similar goals, the same spatial resolution, and the same geographic domain. The daily BCCA application differed in that it featured three variables rather than two (daily precipitation, daily maximum temperature, and daily minimum temperature) and three time domains (1961-2000, 2046-2065, and 2081-2100) rather than one (1950-2099).

1.3 Downscaling CMIP5

Anticipating the release of CMIP5, the Collaborators recognized user interest in having access to an information resource that could: (1) help them understand

[4] BCSD CMIP3 hydrology projections over the Western U.S. are not discussed in this memorandum. To learn more about them, visit: http://www.usbr.gov/WaterSMART/docs/west-wide-climate-risk-assessments.pdf. This memorandum will be edited to describe hydrologic projections development once BCSD CMIP5 hydrology projections over the contiguous U.S. are completed (expected in summer 2013). Summary information from this memorandum is provided on the About page of the DCHP website.

what CMIP5 means for local impacts assessments, and (2) permit them to readily assess how the new information based on CMIP5 compares to the preceding information based on CMIP3. Using support from Reclamation,[5] U.S. Army Corps of Engineers, Lawrence Livermore National Laboratory, and National Aeronautics and Space Administration (NASA) Ames Research Center, a downscaling team from Climate Analytics Group, Climate Central, and Santa Clara University applied monthly BCSD and daily BCCA from the earlier effort to downscale a large collection of CMIP5 global projections. Attributes of this effort are described in Section 2. Subsequently, Reclamation and Lawrence Livermore National Laboratory worked with this downscaling team to import this new content into the DCHP website[6].

1.4 About this Memorandum

The remainder of this memorandum provides a reference for users of the DCHP website. It is organized as follows:

- **Section 2 - About the Downscaled Climate Projections:** This section includes descriptions of downscaling techniques (alluding to appendix A), scope of CMIP3 and CMIP5 downscaling efforts, and responses to frequently asked questions about why these methods were chosen and what their limitations are relative to other techniques that might have been used (alluding to appendix B). This section and its appendices include much of the information describing development of BCSD and BCCA CMIP3 downscaled climate projections included on the predecessor website.

- **Section 3 - Comparing BCSD CMIP5 Versus CMIP3 Information:** This section provides a cursory comparison of the CMIP5 and CMIP3 downscaling results, showing how they are broadly similar but also express locally relevant differences. The comparison is developed using two views: spatially distributed and basin integrated.

- **Section 4 - Improving our Understanding of Downscaled CMIP5 Information:** The final section of the memorandum summarizes ongoing research efforts designed to help the user community understand CMIP5 information and how/why it differs from CMIP3 over some regions.

---

[5] WaterSMART Grant to Develop Climate Analysis Tools, http://www.usbr.gov/WaterSMART/cat/prev.html.
[6] http://gdo-dcp.ucllnl.org/downscaled_cmip_projections.

2. About the Downscaled Climate Projections

This section summarizes scope and development of both downscaled CMIP3 and CMIP5 climate information resources. Both feature: (a) monthly projections of precipitation and daily average temperature developed using BCSD (appendix A); and (b) daily projections of precipitation, daily minimum temperature, and daily maximum temperature using BCCA (appendix A). The downscaled CMIP5 scope also includes monthly BCSD projections of mean daily minimum temperature and mean daily maximum temperature, as well as daily BCCA projections of daily average temperature. This summarizes:

- Scope of CMIP3 and CMIP5 ensemble
- Downscaling techniques (with method details provided in appendix A and frequently asked questions addressed in appendix B)
- Quality assurance applied to development of new downscaled CMIP5 climate resources
- April 30, 2013, notes accompanying the release of downscaled CMIP5 climate resources

2.1 Assembling Projection Ensembles

The assembly of projection ensembles was steered by the goals listed in section 1.2. Those goals call for assembling ensembles that represent a large collection of the global climate models and climate forcing scenarios used in CMIP3 and CMIP5. In addition, they call for inclusion of multiple projections per combination of climate model and climate forcing scenario, obtained by varying initial conditions within an individual model/scenario experiment, as available, recognizing that internal climate system variability is an important component in characterizing local climate projection uncertainty (Hawkins and Sutton, 2009), especially for precipitation (Hawkins and Sutton, 2010; Deser et al., 2010).

Membership of the BCSD and BCCA CMIP3 ensembles is shown in table 1. The corresponding CMIP5 ensembles are described in table 2. The latter ensembles are based on monthly and daily CMIP5 global climate projections made available through the CMIP5 Earth System Grid Federation (Earth System Grid)[7] as of July 2012. In table 1, every run listed in plain text styling is a

[7] http://cmip-pcmdi.llnl.gov/cmip5/data_getting_started.html

member of the monthly BCSD ensemble; *underline-italics* styling indicates that the run is also included in the daily BCCA ensemble. In table 2, the same styling rules apply, along with a third rule that every run in ***bold-underline-italics*** styling indicates that it is part of the daily BCCA ensemble but not the monthly BCSD ensemble.

Table 1. BCSD and BCCA CMIP3 Projection Ensembles

WCRP CMIP3 Climate Modeling Group	WCRP CMIP3 Climate Model ID	SRES[1] A2 runs[2]	SRES A1b runs	SRES B1 runs	Primary Reference
Bjerknes Centre for Climate Research, Norway	BCCR-BCM2.0	1	1	1	Furevik et al., 2003
Canadian Centre for Climate Modeling and Analysis, Canada	CGCM3.1 (T47)	*1-3*, 4-5	*1-3*, 4-5	*1-3*, 4-5	Flato and Boer, 2001
Meteo-France/Centre National de Recherches Meteorologiques, France	CNRM-CM3	*1*	*1*	*1*	Salas-Melia et al., 2005
Commonwealth Scientific and Industrial Research Organization, Atmospheric Research, Australia	CSIRO-Mk3.0	1	1	1	Gordon et al., 2002
U.S. Dept. of Commerce/NOAA/ Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.0	*1*	*1*	*1*	Delworth et al., 2006
U.S. Dept. of Commerce/NOAA/ Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.1	*1*	*1*	*1*	Delworth et al., 2006
NASA/Goddard Institute for Space Studies, USA	GISS-ER	1	2, 4	1	Russell et al., 2000
Institute for Numerical Mathematics, Russia	INM-CM3.0	1	1	1	Diansky and Volodin, 2002
Institut Pierre Simon Laplace, France	IPSL-CM4	*1*	*1*	*1*	IPSL, 2005
Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change, Japan	MIROC3.2 (medres)	*1*, *2*, 3	*1*, *2*, 3	*1*, *2*, 3	K-1 model developers, 2004
Meteorological Institute of the University of Bonn, Meteorological Research Institute of the Korean Meteorological Association, Germany/Korea	ECHO-G	*1-3*	*1-3*	*1-3*	Legutke and Voss, 1999
Max Planck Institute for Meteorology, Germany	ECHAM5/ MPI-OM	1-3	*1*, *2*, 3	*1*, *2*, 3	Jungclaus et al., 2006
Meteorological Research Institute, Japan	MRI-CGCM2.3.2	*1-5*	*1-5*	*1-5*	Yukimoto et al., 2001

Table 1. BCSD and BCCA CMIP3 Projection Ensembles

WCRP CMIP3 Climate Modeling Group	WCRP CMIP3 Climate Model ID	SRES[1] A2 runs[2]	SRES A1b runs	SRES B1 runs	Primary Reference
National Center for Atmospheric Research, USA	CCSM3	1-4	1-3, 5-7	1-7	Collins et al., 2006
National Center for Atmospheric Research, USA	PCM	1-4	1-4	2, 3	Washington et al., 2000
Hadley Centre for Climate Prediction and Research/Met Office, UK	UKMO-HadCM3	1	1	1	Gordon et al., 2000
Number of BCSD Climate Projections = 112 Number of BCCA Climate Projections = *53*		36 *17*	39 *18*	37 *18*	

[1] IPCC (2000).
[2] Runs reflect which CMIP3 historical simulation was used to initialize the given future projection. Such correspondence is indicated at: http://www-pcmdi.llnl.gov/ipcc/time_correspondence_summary.htm.

Table 2. BCSD and BCCA CMIP5 Projection Ensembles

WCRP CMIP5 Climate Modeling Group[1]	WCRP CMIP5 Climate Model ID	RCP 2.6 runs[2]	RCP 4.5 runs	RCP 6.0 runs	RCP 8.5 runs
Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology, Australia	ACCESS1-0		*1*		*1*
	ACCESS1-3		1		1
Beijing Climate Center, China Meteorological Administration	BCC-CSM1-1	*1*	*1*	*1*	*1*
	BCC-CSM1-1-M		1		1
College of Global Change and Earth System Science, Beijing Normal University	BNU-ESM	1	*1*		*1*
Canadian Centre for Climate Modelling and Analysis	CanESM2	*1-5*	*1-5*		*1-5*
National Center for Atmospheric Research	CCSM4	*1-2*, 3-5	*1-2*, 3-5	*1-2*, 3-5	*1-2*, 3-5
Community Earth System Model Contributors	CESM1-BGC		*1*		*1*
	CESM1-CAM5	1-3	1-3	1, 3	1-3
Centro Euro-Mediterraneo per I Cambiamenti Climatici	CMCC-CM		1		1
Centre National de Recherches Météorologiques/ Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CM5		*1*		*1*, 2, 4, 6, 10
Commonwealth Scientific and Industrial Research Organization, Queensland Climate Change Centre of Excellence	CSIRO-Mk3-6-0	*1-10*	*1-10*		*1-10*
EC-Earth consortium, representing 22 academic institutions and meteorological services from 10 countries in Europe	EC-EARTH	8, 12	2, 8, 12		6, 8, 12

Table 2. BCSD and BCCA CMIP5 Projection Ensembles

WCRP CMIP5 Climate Modeling Group[1]	WCRP CMIP5 Climate Model ID	RCP 2.6 runs[2]	RCP 4.5 runs	RCP 6.0 runs	RCP 8.5 runs
Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, and Center for Earth System Science, Tsinghua University	FGOALS-g2	1	1		1
Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences	FGOALS-s2		2		2,3
The First Institute of Oceanography, State Oceanic Administration, China	FIO-ESM	1-3	1-3	1-3	1-3
NOAA Geophysical Fluid Dynamics Laboratory	GFDL-CM3	*1*	*1*	*1*	*1*
	GFDL-ESM2G	*1*	*1*	*1*	*1*
	GFDL-ESM2M	*1*	*1*	*1*	*1*
NASA Goddard Institute for Space Studies	GISS-E2-H-CC		1		
	GISS-E2-R	1	1-5	1	1
	GISS-E2-R-CC		1		
Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)	HadGEM2-AO	1	1	1	1
	HadGEM2-CC		1		1
	HadGEM2-ES	1-4	1-4	1-4	1-4
Institute for Numerical Mathematics	INM-CM4		*1*		*1*
Institut Pierre-Simon Laplace	IPSL-CM5A-LR	*1-3*	*1-4*	*1*	*1-4*
	IPSL-CM5A-MR	*1*	*1*	*1*	*1*
	IPSL-CM5B-LR		1		1
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC-ESM	*1*	*1*	*1*	*1*
	MIROC-ESM-CHEM	*1*	*1*	*1*	*1*
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC5	*1*, ***2-3***	*1*, ***2-3***	*1*	*1*, ***2-3***
Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI-ESM-LR	*1-3*	*1-3*		*1-3*
	MPI-ESM-MR	*1*	*1*, ***2-3***		*1*
Meteorological Research Institute	MRI-CGCM3	*1*	*1*	***1***	*1*
Norwegian Climate Centre	NorESM1-M	*1*	*1*	*1*	*1*
	NorESM1-ME	1	1	1	1
Number of BCSD Climate Projections = 234 Number of BCCA Climate Projections = *134* Number of BCCA Climate Projections (not in BCSD set) = ***9***		54 *36* ***2***	72 *43* ***4***	37 *13* ***1***	71 *42* ***2***

[1] http://cmip-pcmdi.llnl.gov/cmip5/docs/CMIP5_modeling_groups.pdf.

[2] Runs reflect X from a given CMIP5 projection's rXi1p1 identifier, defined at http://cmip-pcmdi.llnl.gov/cmip5/docs/cmip5_data_reference_syntax_v0-25_clean.pdf.

2.2 Climate Projection Downscaling Methods

Appendix A describes and illustrates stepwise procedures for monthly BCSD and daily BCCA, as they were applied to CMIP3 and CMIP5 climate projections. For the most part, the applications to CMIP3 and CMIP5 were consistent. The few exceptions are listed in appendix A, and a couple of them are noted here.

- First, monthly BCSD application begins with the step of regridding global climate projections from model-specific native spatial resolution to a common resolution (i.e., generating "REGRID" projections[8]). In the CMIP3 application, the REGRID resolution was 2º. In the CMIP5 application, the REGRID resolution was 1º. Daily BCCA involves the same initial regridding step, and the REGRID resolutions were also 2º and 1º for CMIP3 and CMIP5 applications, respectively.

- Second, following the regridding step, BCCA CMIP3 application proceeded with bias-correction of daily precipitation, minimum temperature, and maximum temperature, guided by gridded observation datasets (Maurer et al. 2002, appendix A). BCCA CMIP5 application proceeded with bias-correction of precipitation, maximum temperature, and diurnal temperature range (DTR); bias-corrected minimum temperature was derived using the latter two outputs. This modification to the BCCA application was motivated by recognition during the CMIP3 application that the former approach permitted bias-corrected minimum temperatures to exceed bias-corrected maximum temperatures. Whenever this happened in CMIP3 application (by day and location), the values were switched. The modified approach for BCCA CMIP5 eliminates that issue.

During the course of serving monthly BCSD and daily BCCA CMIP3 projections from the predecessor website, users began to submit questions through the website's "Forum" page. Many of these questions began to fall under common themes. Responses to these questions were assembled under the heading of "Frequently Asked Questions" and are provided in appendix B. These questions include:

- What other downscaling methodologies might have been used?

- How does the BCSD methodology contrast from other methods, and what are its relative strengths and weaknesses relative to other methods?

- How do BCSD and BCCA compare with one another?

[8] As explained in appendix A, REGRID precedes the two steps of BCSD: bias-correction at the coarser REGRID resolution to produce bias-corrected (BC) projections, and spatial disaggregation of BC to the finer resolution BCSD projections.

- What are some planning applications that might be supported by monthly BCSD and daily BCCA climate projections?
- What are some uncertainties associated with using BCSD and BCCA climate projections, and how might the level of confidence in projection use vary by application?

2.3 Quality Assurance

Several checks were performed to ensure that the downscaling algorithms were properly applied and that the downscaled projections were developed as intended. First, prior to production, the BCSD downscaling code was consolidated from multiple languages and routines into a single-language NCL[9] implementation, and then it was checked for reproducibility relative to the old multilanguage code. Comparison of downscaled results using both code versions showed a close match with only minor differences (e.g., mean absolute differences of all values [all times steps and grid cells] were 0.04 millimeters per day [mm/day] for precipitation and 0.05 degrees Celsius (ºC) for average surface temperature). To check the significance of these differences, spatial-mean time series were computed from both sets of results over two test basins (i.e., Colorado River above Lees Ferry; and a smaller headwaters area within the basin containing roughly 30 grid cells, or an area of roughly 60 km by 72 km). Comparisons of the spatial-mean time series showed nearly exact matches (e.g., precipitation differences were <=0.01 mm/day). The BCCA code had already undergone this language consolidation and reproducibility check during its application to CMIP3. Additional checks were required for its CMIP5 application to verify that the bias-correction of DTR, rather than daily minimum temperature, performed as expected.

During production,[10] checks were performed to verify data integrity of global climate model (GCM) input, which was found to be necessary as some global climate modeling centers uploaded projection results files to the Earth System Grid that were incomplete, corrupted, or indexed in some mistaken fashion. Such projections were culled from the ensemble if such problems were found. Checks were also performed on the downscaling output (e.g., verifying number of grid cells per file, number of time steps per file, start and end dates of each file).

[9] NCAR Command Language (http://www.ncl.ucar.edu/index.shtml).

[10] This dataset was produced using the NASA Earth Exchange (NEX) (https://c3.nasa.gov/nex/), a "science as a service" collaborative for the geosciences community. NEX combines state-of-the-art supercomputing, Earth system modeling, remote sensing data from NASA and other agencies, and a scientific social networking platform to deliver a complete work environment in which users can explore and analyze large Earth science data sets, run modeling codes, collaborate on new or existing projects, and share results within and/or among communities.

These checks were necessary given that computing interruptions were possible during downscaling and/or during file input/output operations. Additional checks on the downscaling output included checking the number of grid cells with rain at each time step per precipitation file, number of grid cells with no rain at any time step per precipitation file, maximum temperature in each temperature file, and number of cells with temperature over 50 ºC in each temperature file. These latter checks were done to identify potential artifacts and questionable extremes.

After production, Reclamation independently implemented the two downscaling codes in another computing environment to perform a second check on reproducibility and to check whether results were dependent on computing environment. The BCSD code was applied to two 1º REGRID projections (appendix A) of the CMIP5 projection ensemble. Results for the resultant 1º bias-corrected (BC) projections (appendix A) and 1/8º BCSD projections were compared against those developed by the production team and showed an exact match. Likewise, the BCCA code was applied to one 1º REGRID projection of the CMIP5 ensemble. Comparison of 1/8º BCCA results from the production team with this application showed an exact match.

Collectively, these checks prior to, during, and after production indicate that the downscaling algorithms were implemented as intended. That said, all uses of these projections are predicated on the following Disclaimer (also shown on the DCHP website's home page):

> *"These projections are being made available for the convenience of interested persons. The content developers (Climate Analytics Group, Climate Central, Lawrence Livermore National Laboratory, Reclamation, Santa Clara University, Scripps Institution of Oceanography, U.S. Army Corps of Engineers, and U.S. Geological Survey) believe the information to be correct representations of potential high-resolution climate/hydrologic variations and changes subject to the limitations of the CMIP3 and CMIP5 global climate simulations and of the downscaling methods utilized. However, human and mechanical errors remain possibilities. Therefore, the content developers do not guarantee the accuracy, completeness, timeliness, or correct sequencing of the information. Also, neither the content developers, nor any of the sources of the information shall be responsible for any errors or omissions, or for the use or results obtained from the use of this information."*

2.4 Release Notes (May 7, 2013)

Moving forward, it is expected that this memorandum will serve as a living document describing the Collaborators' information resources and DCHP website contents pertaining to downscaled climate projections. At the time of this DCHP website release, the following notes apply to the release of the downscaled CMIP5 climate projections:

- The CMIP5 projections represent a new opportunity to improve our understanding of climate science, which is evolving at a rapid pace. As new information such as CMIP5 is developed, the Collaborators are taking active roles in evaluating and incorporating it, as appropriate, into ongoing activities.

- While CMIP5 projections may inform future analyses, many completed and ongoing studies remain informed by CMIP3 projections that were selected as best information available at the time of study. Even though CMIP5 is newer, it has not been determined to be a better or more reliable source of climate projections compared to existing CMIP3 climate projections. CMIP5 projections should be considered an addition to (not a replacement of) the existing CMIP3 projections unless the climate science community can offer explanation as to why CMIP5 should be favored over CMIP3.

- Because the CMIP5 model solutions have been available to the wider community only very recently, understanding how and why CMIP5 results differ from those in CMIP3 is at the early stage. It is thought now that any differences broadly relate to updates and other differences in the climate models used for CMIP5 and to the new set of climate forcing emissions scenarios. However, understanding those differences and their effects on regional specific is still underway.

- Section 3 provides a cursory summary of differences between downscaled CMIP5 and CMIP3 climate projections over the conterminous U.S. Most of the differences arise from differences in the CMIP5 GCM projections of regional scale temperature and precipitation. However, some of these differences are due to the downscaling technique, meaning that the differences in downscaled information are similar to, but not precisely the same as, differences in global CMIP5 and CMIP3 climate information over the U.S. prior to downscaling.

- Collaborators are releasing the CMIP5 content additions at the DCHP website with the goal of accelerating community understanding of the CMIP5 versus CMIP3 differences depicted here and promoting the use of an ever more complete representation of possible future climates. Releasing the new information to the large user community will build shared awareness of CMIP5 versus CMIP3 similarities and differences and enhance the encouragement of the large community of users already familiar with CMIP3 to evaluate, explore, and diagnose the projections.

3. Comparing BCSD CMIP5 Versus CMIP3 Information

This section offers a cursory comparison of downscaled CMIP5 and CMIP3 climate projections. The purpose is to orient users on the more noticeable similarities and differences over various regions of the contiguous U.S. Characterization of more localized differences is an activity left to the reader, aided by using the DCHP website's functionality, which enables the request of data-subsets by variable, projections, geographic, and time period.

This comparison only considers the monthly BCSD ensembles. This is due to two reasons. First, most of the predecessor website's data requests have involved subsets of monthly BCSD CMIP3 projections, even after release of the daily BCCA CMIP3 climate projections. Second, Maurer et al. (2010) showed that at the monthly level, BCSD and BCCA (aggregated from daily to monthly) show roughly similar results. Therefore, BCCA CMIP5 (BCCA5) versus BCCA CMIP3 (BCCA3) comparisons should be roughly similar to that of BCSD CMIP5 (BCSD5) and BCSD CMIP3 (BCSD3) at the monthly level. We note, however, that the BCCA5 and BCCA3 ensembles are only subsets of the BCSD5 and BCSD3 ensembles. If one wishes to determine whether BCCA5 versus BCCA3 differences are similar to those of BCSD5 versus BCSD3, the evaluation should be done with focus on common sets of CMIP3 and CMIP5 global climate projections in table 1 and table 2, respectively. Finally, readers interested in how submonthly features of BCCA CMIP5 compare to those of BCCA CMIP3 are invited to conduct similar evaluations outlined in this section, but for submonthly statistics (e.g., changes in extreme daily precipitation in the BCCA CMIP3 ensemble, shown in Brekke and Barsugli [2012]).

The comparison is developed using two views: spatially distributed and basin integrated. The first view addresses questions that invite inspection of the spatial distributions of differences over the Western United States. The second view provides a sense of how locally specific differences integrate into yield changes over regions of interest, which might be more relevant for user purposes. The basin-integrated view is demonstrated using the Upper Colorado Basin (i.e., Colorado River basin above Lees Ferry, Arizona) and complemented with a set of similar analyses integrated over other Western U.S. basins (appendix C):

- Upper Klamath (Klamath River near the California/Oregon border)
- Upper Missouri (Missouri River near Milk River confluence, Montana)
- North Fork Platte (North Fork Platte River near Lake McConaughy, Nebraska)

- South Fork Platte (South Fork Platte River near Lake McConaughy, Nebraska)
- Upper Rio Grande (Rio Grande at Elephant Butte Dam, New Mexico)
- Sacramento (Sacramento River near Freeport, California)
- Lower San Joaquin (San Joaquin River near Vernalis and below Mendota Pool, California)
- Upper Snake (Snake River at Brownlee, Idaho)
- Truckee (Truckee River at Nixon, Nevada)

Finally, several user needs were identified during these evaluations and are noted in the discussion. The purpose is to call attention to these needs so that they might be addressed by the research community.

3.1 Spatially Distributed Changes

This section addresses the following questions about how spatially distributed climate changes compare and contrast for the BCSD5 and BCSD3 projections:

- How are the central-tendency climate changes similar and different by the mid-21st century?
- Where differences occur, are they expressed consistently throughout the 21st century?
- Where differences occur, do they have different dependences on the two steps of BCSD?
- How are the central-tendency precipitation changes similar and different when we focus on the highest emissions scenarios and results before and after BCSD?

Note that for the purposes of this report, the term "central tendency" refers to median values from the climate projection ensemble, or ensemble-median values.

How are the central-tendency climate changes similar and different by the mid-21st century?

In this comparison, the data sources were BCSD3 and BCSD5. For each source, a three-step evaluation was performed:

1. Compute change in 30-year mean annual precipitation and temperature from 1970-1999 to 2040-2069 for each projection and grid cell in the BCSD domain (i.e., contiguous U.S., southern Canada, and northern Mexico).

2. At each grid cell, pool the projected changes by climate model and average them, resulting in a model-specific spatially distributed change pattern (i.e., model pattern).

3. Pool the model patterns and identify the ensemble-median change at each grid cell (i.e., from 16 BCSD3 model patterns and from 37 BCSD5 model patterns).

The procedure could have been done with steps 2 and 3 replaced by a single step of identifying ensemble-median changes across all projections in the ensemble. The potential difficulty with this alternative approach is that it would weigh the ensemble median in favor of climate modeling groups that generated more climate projections with their model(s), solely because of their greater productivity. On the other hand, collapsing information into model patterns sets up comparison of patterns that are unequally representative, with the model patterns from the more prolific modeling groups being more robust and less variable than the model patterns from groups that provided fewer projections (e.g., Are the patterns expressions of climate variability or actual climate change responding to the climate forcing scenario?). Evaluation of CMIP3 projections (Pierce et al., 2009) did show that additional runs from a single climate model tend to be less independent than runs by different climate models. This suggests that users should be cautioned against counting multiple runs with the same climate model as equal to runs by different climate models. Nevertheless, no resolution to this tradeoff of equal projection weighting versus equal model weighting is offered in this discussion. The decision to follow the three-step process was ultimately subjective. However, as will be shown in the basin-integrated view, the choice of approach may not be critical for portraying ensemble-median changes over larger regions.

Another important aspect of this approach is that climate projections from disparate climate forcing emissions scenarios are being pooled together into respective CMIP3 and CMIP5 "ensembles of opportunity." As indicated in Section 2, the BCSD CMIP3 application represents climate projections forced by three SRES GHG emissions scenarios (IPCC, 2000): SRES B1, A1B, and A2. The BCSD CMIP5 application considers climate projections forced by four RCPs (van Vuuren et al., 2011): RCPs 2.6, 4.5, 6.0, and 8.5. Without going into the specifics of how the SRES and RCP scenarios were developed, one may draw impressions about their aggregate implications for global climate by evaluating projected global mean air temperature under each scenario (figure 1). It is evident that the group of four RCPs considered in the BCSD CMIP5 application leads to global mean temperature responses that encompass CMIP3 responses associated with the three SRES scenarios. Put another way, the BCSD CMIP5 application considers emissions paths that are higher (RCP 8.5) and lower (RCP 2.6) than comparable extreme SRES paths in the BCSD CMIP3 application (A2 and B1, respectively). In particular, RCP2.6 features a strong mitigation assumption, with emissions peaking in the middle of the century and then becoming negative later on, thus causing concentrations of GHGs and, consequently, temperature changes to decrease in the second part of the 21st century. No such mitigation scenario was assumed among the SRES run by CMIP3. This helps build expectation that the family of BCSD5 temperature projections may include warmer and cooler projections than those featured among the BCSD3 temperature projections.

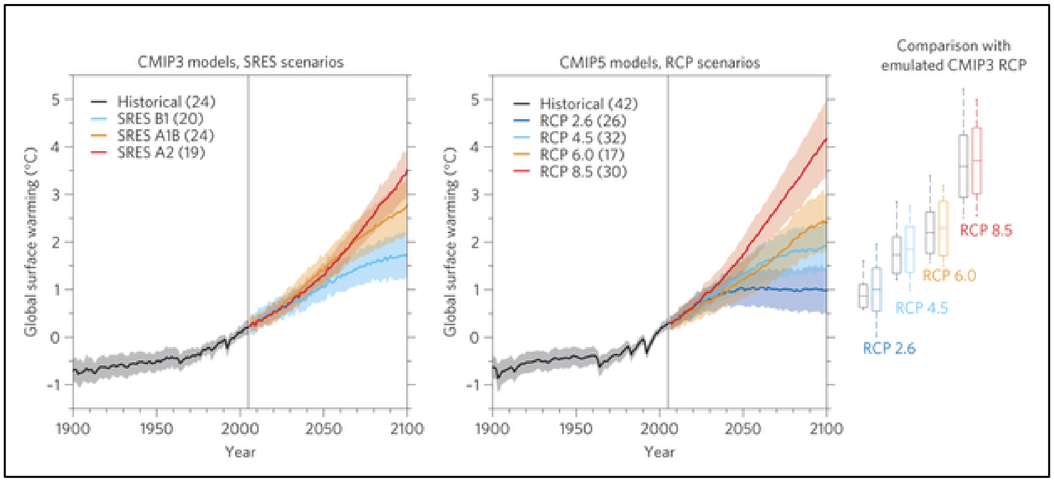

Figure 1. Comparison of global mean temperature projections from CMIP3 and CMIP5. (Figure courtesy of Knutti and Sedláček [2012].[11])

To summarize, the subsequent discussion of results begins with focus on ensemble-median changes found in a multi-emissions, multi-model "ensemble of opportunity." While this approach does encompass the available range of future climate projections, which may be an interest shared by many of the DCHP website users, it also complicates comparison of the CMIP3 and CMIP5 projection ensembles. Users should be aware that some of this complication can be mitigated by comparing CMIP3 and CMIP5 projections developed under more comparable future emissions pathways (and examples of this do follow in

[11] Figure 1 shows global temperature change (mean and one standard deviation as shading) relative to 1986–2005 for the SRES scenarios run by CMIP3 and the RCP scenarios run by CMIP5. The number of models is given in brackets. The box plots (mean, one standard deviation, and minimum to maximum range) are given for 2080–2099 for CMIP5 (colors) and for the MAGICC model calibrated to 19 CMIP3 models (black), both running the RCP scenarios. MAGICC stands for Model for the Assessment of Greenhouse-gas Induced Climate Change, and is described at: http://www.cgd.ucar.edu/cas/wigley/magicc/.

sections 3.1 and 3.2). Users may also refer to the literature (see, for example, Mote et al., 2011) when assembling an ensemble of GCM projections for recommendations on issues such as how many or which GCMs to include.

Precipitation and temperature results from applying the three-step procedure to CMIP5 (BCSD5) and CMIP3 (BCSD3) are shown in the first two rows of figure 2. Results from BCSD5 and BCSD3 show similar change features across the BCSD domain. For example, warming is comparable throughout, precipitation trends toward wetter conditions at higher latitudes and over the Eastern U.S., and precipitation also trends toward drier conditions over portions of the Southwestern U.S. There are also differences. For temperature, the BCSD5 warming trends are more rapid than those from BCSD3 at higher latitudes to the northwest. For precipitation, BCSD5 shows less precipitation increase over the northern Great Plains and the Midwest. It also trends toward drier conditions over a smaller portion of the Southwestern U.S., leaving a greater portion of the Western U.S. trending toward wetter conditions. On this shift in how much of the West is trending toward drier or wetter conditions, BCSD3 and BCSD5 still project wetter conditions to the northwest and drier conditions to the southwest. However, the even-odds line, where an equal number of model patterns are wetter versus drier (i.e., the white-colored boundary between blue areas reflect a wetter majority, and red areas reflect a drier majority) has migrated south in BCSD5 relative to BCSD3. This means that the sign of ensemble-median change went from negative to positive over much of California, the Great Basin, and the upper Colorado River Basin. It can also be seen that much of the area showing the most significant shift from drier to wetter conditions occurs over arid reaches of the intermountain west, where baseline precipitation amounts are already very small (e.g., Great Basin and Upper Colorado basin lower elevations show up as dark blue on panel 5 of figure 2). The extent to which these precipitation increases in arid areas affect basin-integrated precipitation change will be discussed in Section 3.2.

- **User Need:** Understanding why CMIP5 projected changes in annual climate differ from those in CMIP3, and the extents to which these differences are attributable to changes in global climate model composition and/or use of different climate forcing emissions scenarios.

Where differences occur, are they expressed consistently throughout the 21st century?

To address this question, the preceding evaluation was repeated for two other 21st century periods: 2010-2039 and 2070-2099, and BCSD5 versus BCSD3 difference maps were generated. Figure 3 shows the difference maps for all three future periods. Tracking the map features through the periods, it is evident that the spatial pattern of differences is generally consistent from early to late

21st century. This is potentially an indication that where they exist, they generally begin to emerge in the early 21st century, with the sign of difference remaining consistence through the century, and become greater in magnitude as the 21st century proceeds. Of course, there are exceptions to these general observations as one inspects results over smaller area locations.

Where differences occur, do they have different dependences on the two steps of BCSD?

The BCSD procedure yields two intermediate results during the translation of global climate projections at native spatial resolution into downscaled climate projections at 1/8º resolution (appendix A):

- **REGRID projections:** Each climate projection's output interpolated from the source model's native spatial resolution to a common coarse-resolution grid. As explained in section 2.2, the common resolution used for the CMIP3 analysis was 2º; for CMIP5, it was 1º. Results from this step are referenced hereafter as REGRID3 and REGRID5, respectively. They should be viewed as close approximations of uncorrected global climate simulation results over the domain.

- **BC projections:** Informed by results from a common period of historical observation and simulation, each REGRID projection was translated into a BC projection following the quantile-mapping procedure described in appendix A. The procedure yields BC projections at the same coarse resolution as REGRID, hereafter referred to as BC3 and BC5.

This effect of bias-correction can be identified by comparing change patterns from REGRID to BC results. This effect is illustrated and discussed for precipitation projections in figure 4. Temperature changes were also evaluated, but the REGRID5-to-BC5 versus REGRID3-to-BC3 differences were less substantial than those involving precipitation. This might be expected because bias-correction of temperature projections involves constraining the future BC and REGRID trends to be the same (appendix A). Such trend preservation is not a feature of BCSD's bias-correction of precipitation projections, and it has been shown (Reclamation, 2011) that this approach in BCSD CMIP3 application tended to shift REGRID precipitation trends toward wetter BC trends by up to a few percent. Switching to the BCSD CMIP5 application, the same effect is generally evident (see middle row of figure 4). However, inspection of the difference maps (bottom row of figure 4) shows that this trend toward wetter results seems to be greater in the CMIP5 application than in the CMIP3 application over many locations (Southern California, Great Basin, Rocky Mountains, and southern Great Plains).

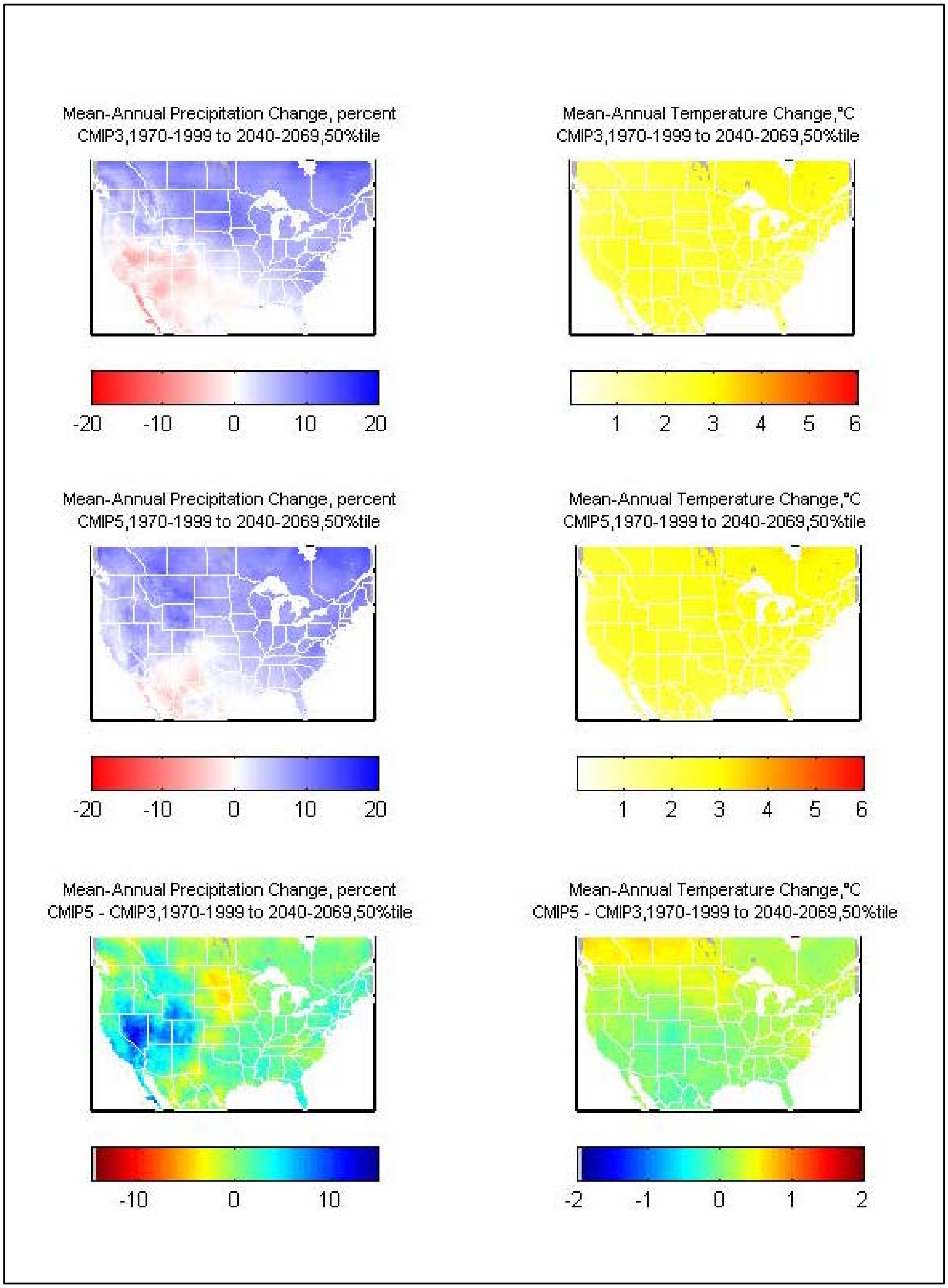

Figure 2. Central tendency changes in mean annual precipitation and temperature over the contiguous U.S. from 1970-1999 to 2040-2069 for BCSD3, BCSD5, and difference. Top and middle rows both show ensemble-median change from model-specific change patterns, informed by three SRES emissions scenarios for CMIP3 (table 1) and four RCP emissions scenarios for CMIP5 (table 2). Bottom row is the difference between the top and middle rows.

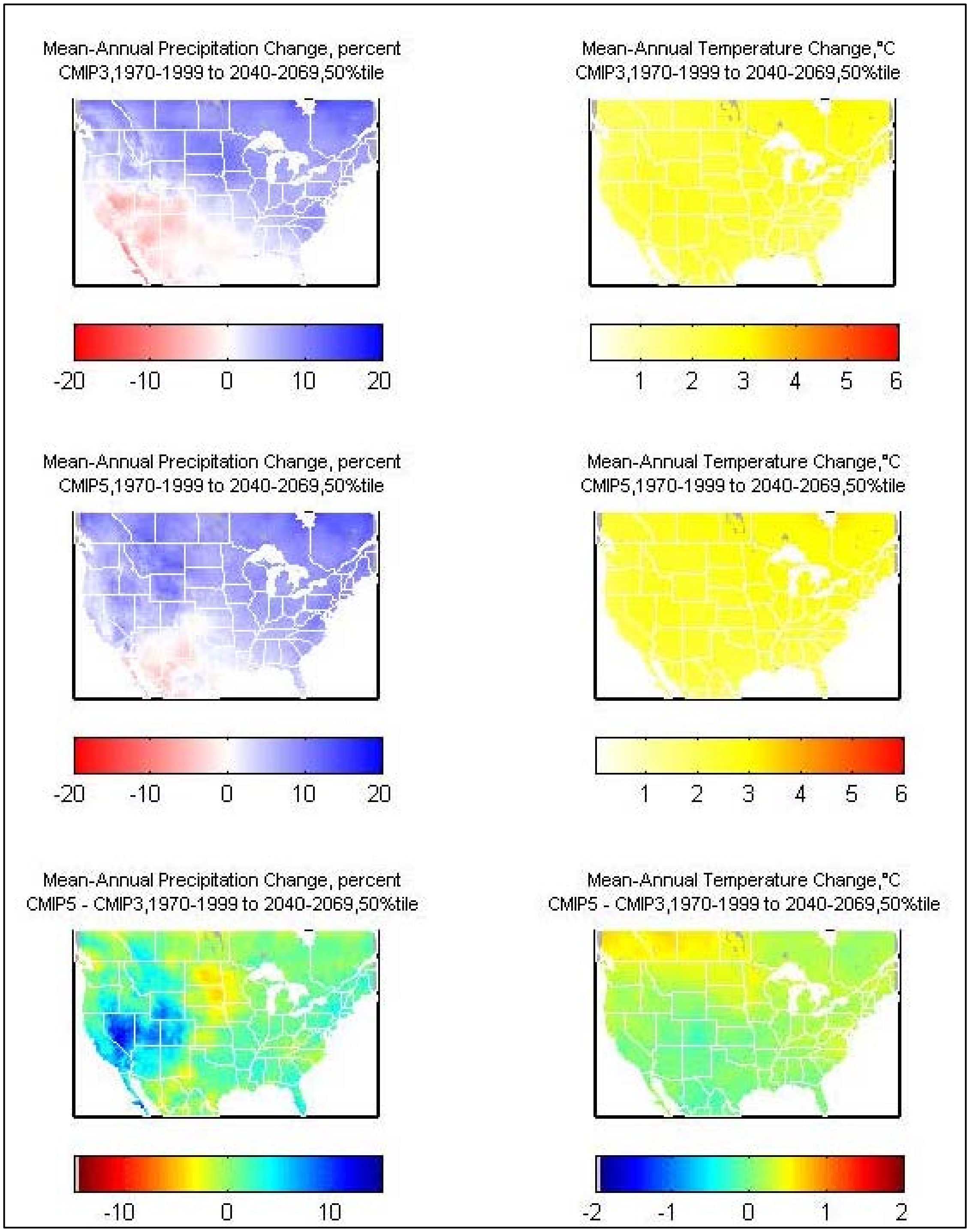

Figure 3. Differences in central tendency changes in mean annual precipitation and temperature over the contiguous U.S. from 1970-1999 to 2010-39, 2040-2069, and 2070-2099, respectively. Maps show difference in the ensemble-median change from model-specific change patterns, informed by three SRES emissions scenarios for CMIP3 (table 1) and four RCP emissions scenarios for CMIP5 (table 2).

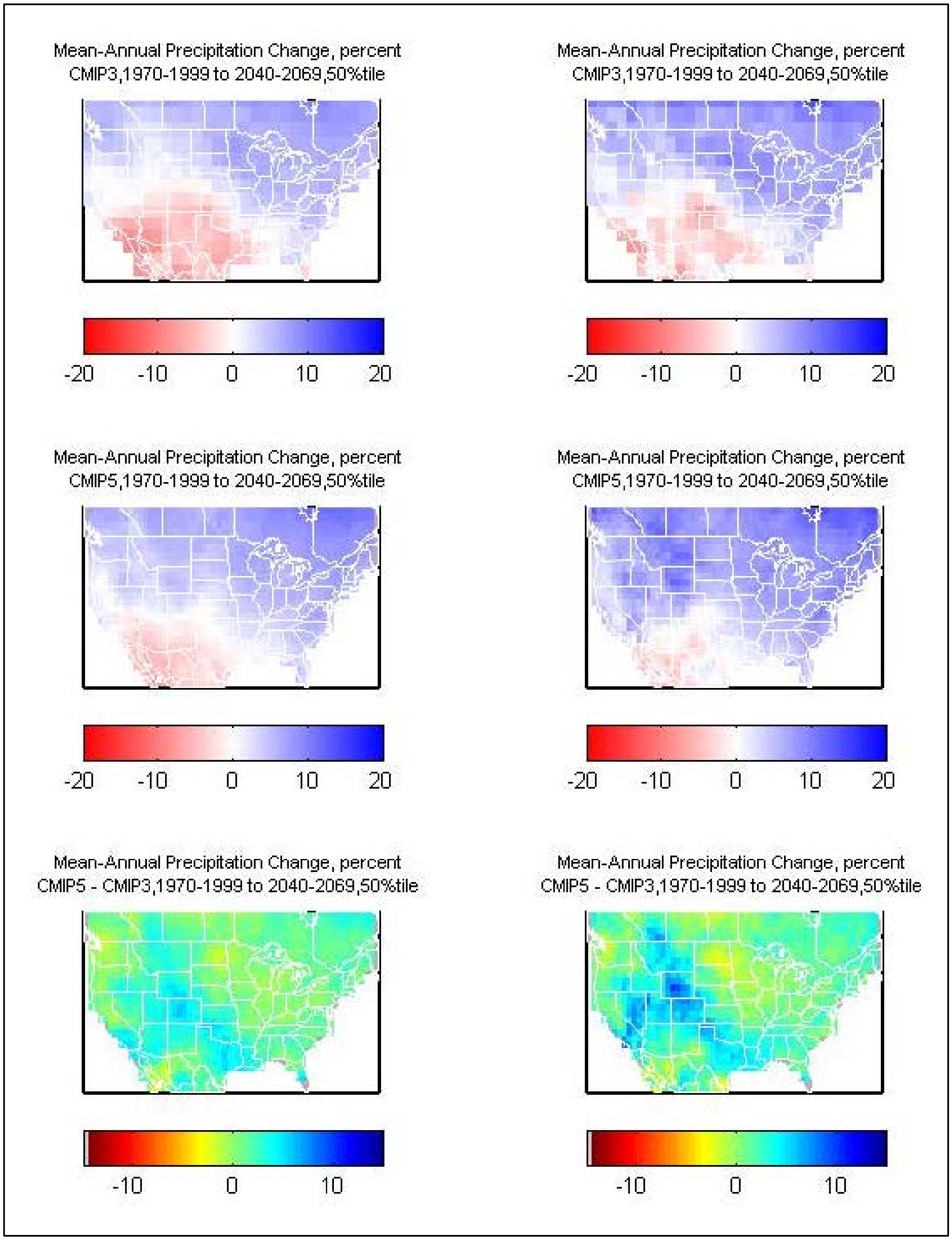

Figure 4. Central tendency changes in mean annual precipitation over the contiguous U.S. from 1970-1999 to 2040-2069 from biased (REGRID) to BC projections. Top and middle rows both show ensemble-median change from model-specific change patterns, informed by three SRES emissions scenarios for CMIP3 (table 1) and four RCP emissions scenarios for CMIP5 (table 2). Bottom row is the difference between the top and middle rows. Left column shows REGRID changes. Right column shows BC changes.

- **User Need:** Understanding why the quantile-mapping bias-correction scheme used in BCSD and BCCA resulted in wetter results in the CMIP5 application compared to the CMIP3 application.

The effect of spatial disaggregation can be examined by comparing change patterns from BC to BCSD. Figure 5 shows that spatial disaggregation modulates precipitation's spatial pattern of change. For some locations, it appears that more modulation comes from the spatial disaggregation technique than from the bias-correction technique. For other locations, the opposite appears to be the case.

- **User Need:** Understanding the respective roles of quantile-mapping bias-correction and spatial disaggregation in modulating the intensity and spatial pattern of annual climate change from REGRID to BCSD projections.

How are the central-tendency precipitation changes similar and different when we focus on the highest emissions scenarios and results before and after BCSD?

We are interested in detecting whether the temperature and precipitation changes associated with the most aggressive emissions scenarios of the new and old downscaled climate projections are appreciably different (i.e., SRES A2 and RCP 8.5 for the CMIP3 and CMIP5 downscaling applications, respectively). This exercise was done for both REGRID and BCSD temperature projections (figure 6) and precipitation projections (figure 7). It was expected that the ensemble of RCP 8.5 temperature projections would be warmer than the ensemble of SRES A2 projections, based on comparison of global mean results (figure 1). Comparison of REGRID and BCSD results over the downscaling domain shows this largely to be the case, although there is some spatial variability in how REGRID5 and BCSD5 differ from REGRID3 and BCSD3. For example, farther north in the domain, warming is greater under RCP 8.5 with use of the CMIP5 climate models than under A2 with CMIP3 models. But generally, warming is the same over southern and central portions of the domain. The geographic pattern of precipitation differences between REGRID5 and REGRID 3 under these high emissions scenarios is broadly similar to that found when all scenarios were pooled (figure 4, left column), albeit with different magnitudes of difference (e.g., greater positive difference along the Rocky Mountain crest). Likewise, the geographic pattern of BCSD5 and BCSD3 differences in precipitation under these high emissions scenarios is broadly similar to that found when pooling all scenarios (figure 2, left column). **However, narrowing our consideration to the high emissions scenarios** leads to some significant modulation of the differences in change patterns with greater positive differences over much of the intermountain West.

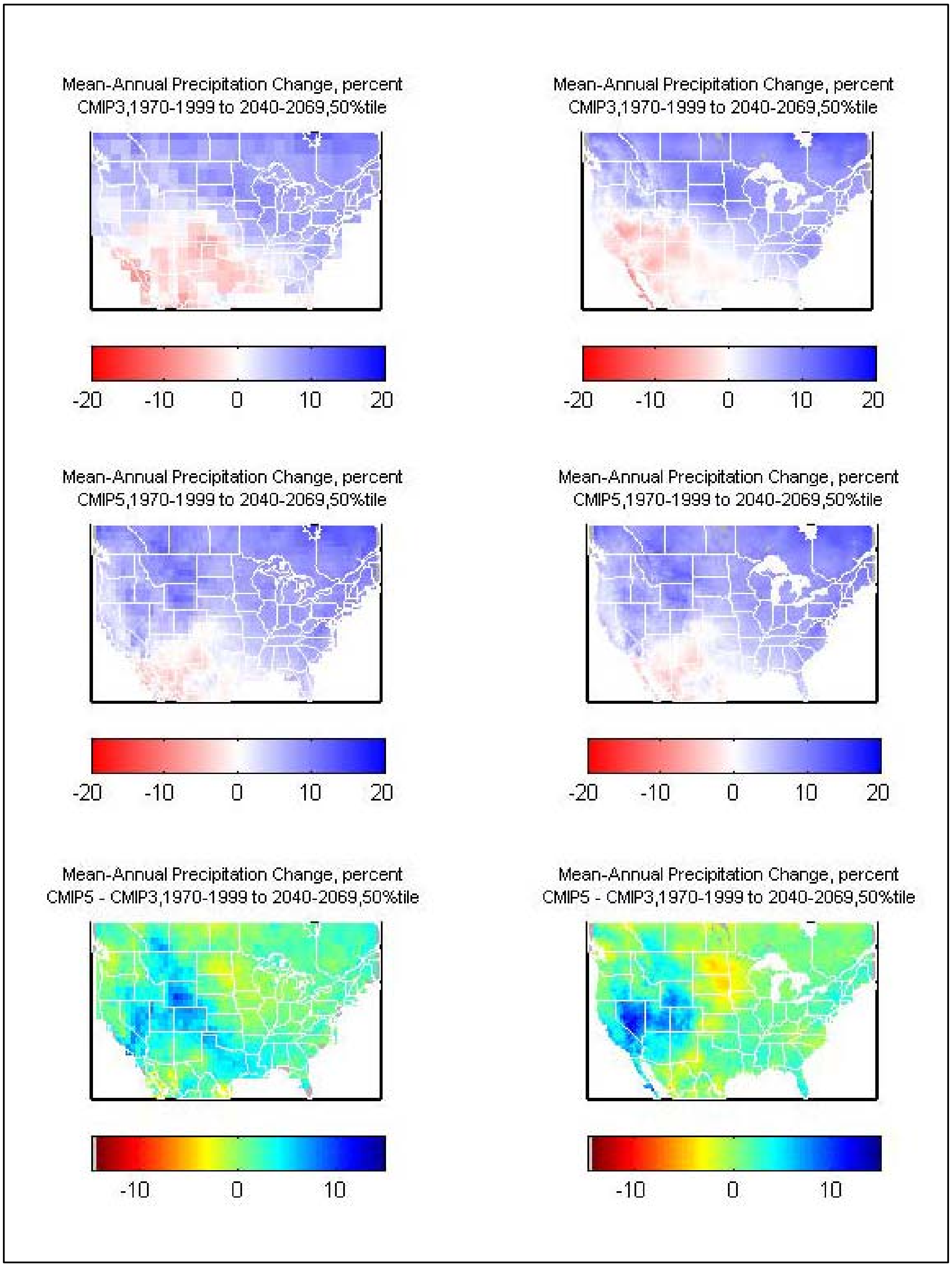

Figure 5. Central tendency changes in mean annual precipitation over the contiguous U.S. from 1970-1999 to 2040-2069 from BC to BCSD projections. Top and middle rows both show ensemble-median change from CMIP5 model-specific change patterns, informed by three SRES emissions scenarios for CMIP3 (table 1) and four RCP emissions scenarios for CMIP5 (table 2). Bottom row is the difference between the top and middle rows. Left column shows BC changes. Right column shows BCSD changes.

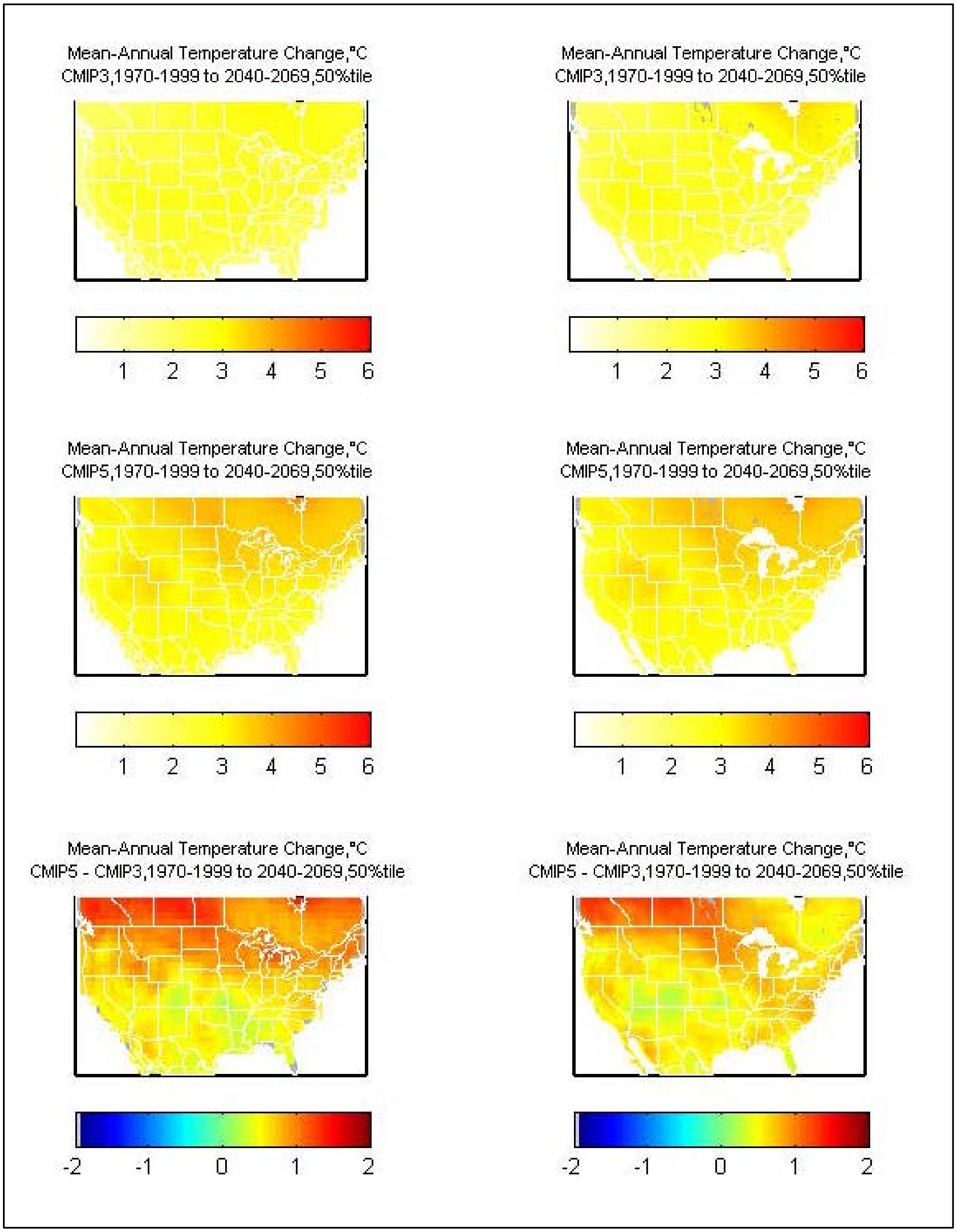

Figure 6. Central tendency change in mean annual temperature over the contiguous U.S. from 1970-1999 to 2040-2069 for REGRID and BCSD projections, focusing on high emissions scenarios only. Top and middle rows both show ensemble-median change from model-specific change patterns, informed by SRES A2 emissions scenario for CMIP3 (table 1) and RCP 8.5 emissions scenario for CMIP5 (table 2). Bottom row is the difference between the top and middle rows. Left column shows REGRID changes. Right column shows BCSD changes.

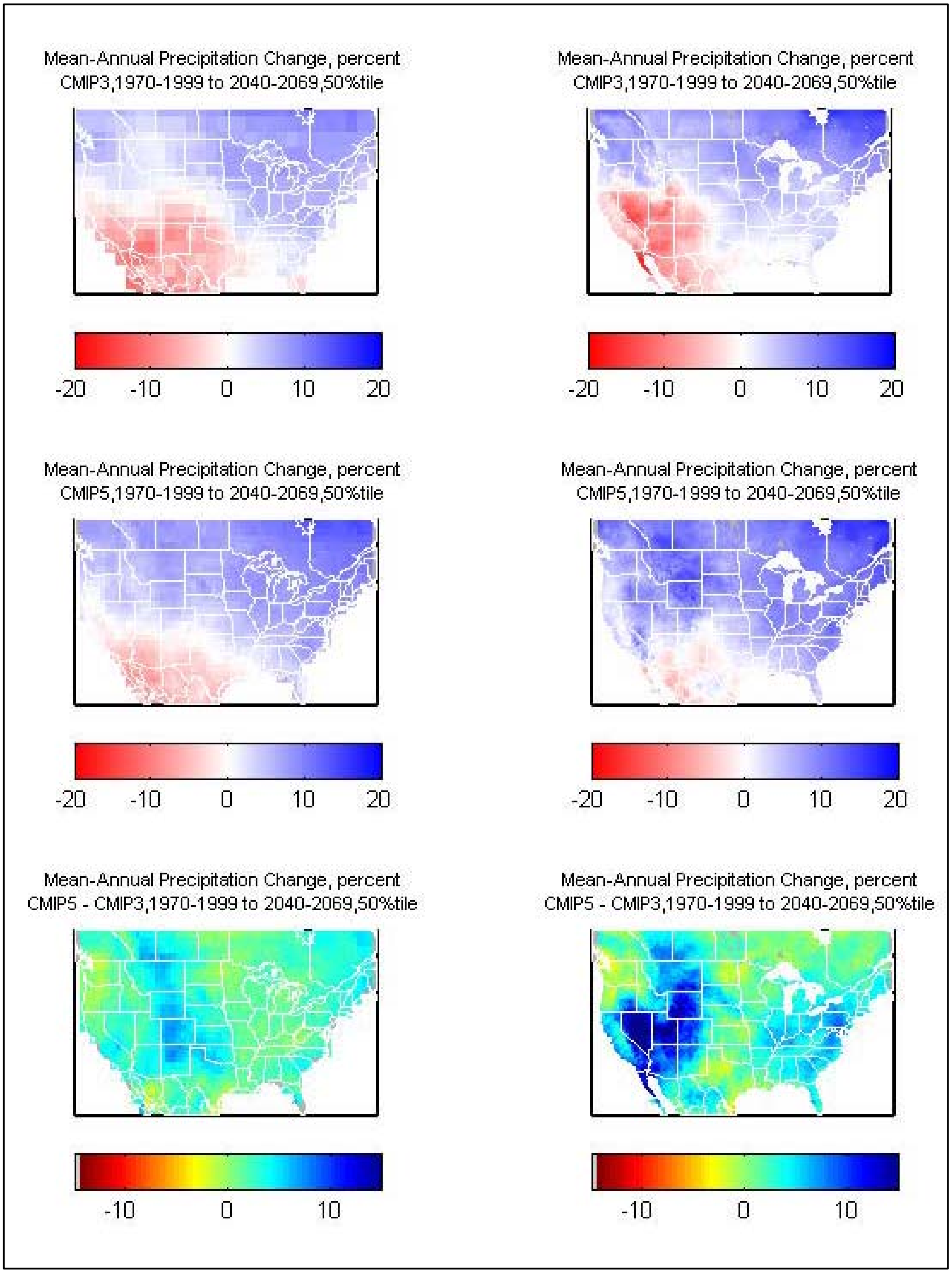

Figure 7. Central tendency change in mean annual precipitation over the contiguous U.S. from 1970-1999 to 2040-2069 for REGRID and BCSD projections, focusing on high emissions scenarios only. Top and middle rows both show ensemble-median change from model-specific change patterns, informed by SRES A2 emissions scenario for CMIP3 (table 1) and RCP 8.5 emissions scenario for CMIP5 (table 2). Bottom row is the difference between the top and middle rows. Left column shows REGRID changes. Right column shows BCSD changes.

User Need: Understanding how the differences between downscaled CMIP5 and CMIP3 projections are sensitive to the choice of emissions scenario.

3.2 Basin-Integrated Changes (Upper Colorado Basin)

This section addresses questions about how basin-integrated climate changes from BCSD5 and BCSD3 compare and contrast. This evaluation is illustrated using the Upper Colorado Basin as a case study (figure 8). Results for other Western U.S. basins are provided in appendix C. Questions considered in this evaluation are:

- How do basin-scale climate changes compare and differ by the mid-21st century?
- Does climate model balancing affect distribution differences?
- Do the two steps of BCSD affect results?
- Does separation of results by emissions scenario affect results?
- How are the central-tendency monthly climate changes similar and different by the mid-21st century?

How do basin-scale climate changes compare and differ by the mid-21st-century?

We initially focus on BCSD3 and BCSD5 basin-integrated change in mean annual precipitation and mean daily average temperature (figure 9). In this evaluation, a three-step procedure similar to that described in section 3.1 was applied, but with a modified first step:

1. Compute change in 30-year mean annual precipitation and temperature from 1970-1999 to 2040-2069 for each projection and grid cell in the Upper Colorado Basin, and then average the grid cell changes to produce a single basin-integrated change for each projection.

2. Pool the projected changes by climate model and average them, resulting in a model-specific basin-integrated change (i.e., model change).

3. Pool the model changes and identify the ensemble median (i.e., from 16 BCSD3 model changes and from 37 BCSD5 model changes).

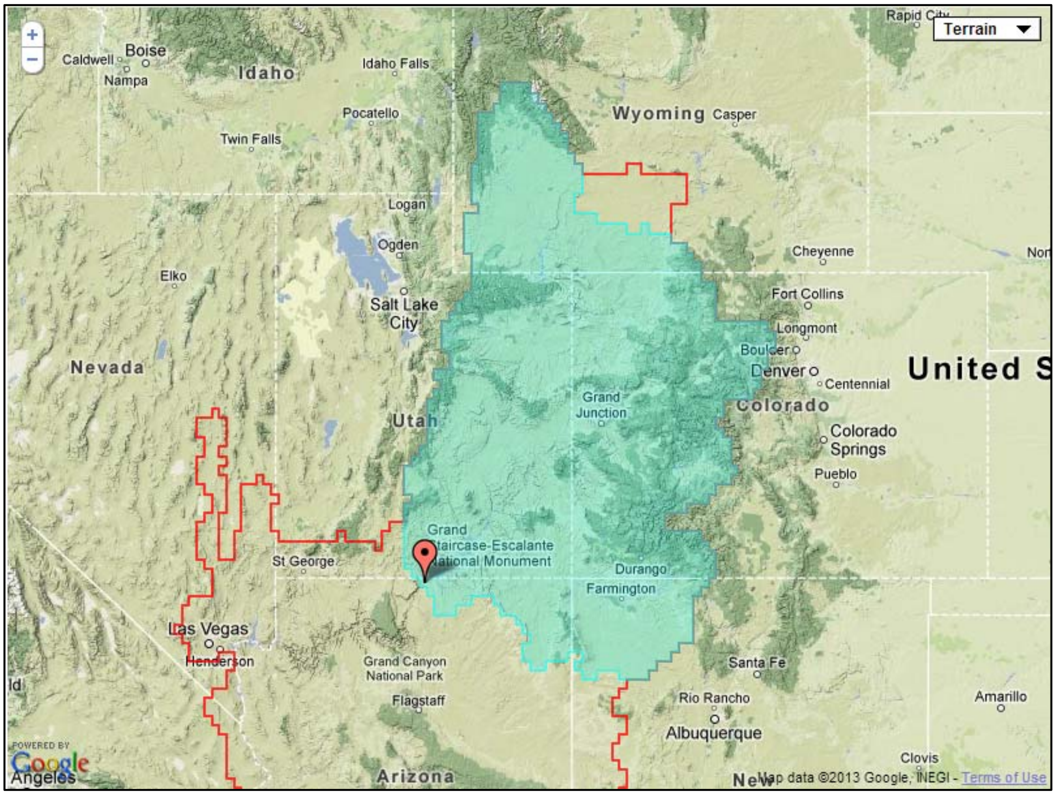

Figure 8. Upper Colorado Basin delineated within the DCHP website's interface for submitting data subset requests.

As in section 3.1, the evaluation first focuses on the multi-emissions, multi-model "ensemble of opportunity." Subsequent evaluation considers results on an emissions scenario-specific basis.

For temperature, figure 9 shows that the BCSD3 and BCSD5 changes over the upper Colorado River Basin are very similar in terms of central tendency (i.e., change at the 50th percentile in each distribution) and spread (e.g., comparison of changes at the 20th and 80th percentiles in each distribution). There is more spread under BCSD5, which is consistent with information shared in section 3.1 about CMIP5 featuring a larger spread of temperature projections due to consideration of a broader range of emissions scenarios (figure 1).

Figure 9 shows distributions of projected changes in mean daily minimum and daily maximum temperatures. These minimum and maximum temperatures show ranges and central tendencies similar to those of mean daily average temperatures. For precipitation, the spread is generally similar in the two ensembles, although there is some indication that the spread is greater in BCSD5, potentially due to the bias-correction wettening effect discussed in section 3.1. However, the BCSD5 distribution is wetter than the BCSD3 distribution at all percentiles, and more so for the above-median percentiles. Notice that the difference in ensemble-median basin-integrated change is roughly 4 percent, which is smaller than some of the spatially distributed changes in the Upper Colorado Basin (e.g., figure 2 shows differences between 5 and 10 percent over much of the basin). This suggests that differences are smaller in grid cells contributing relatively more to the basin average precipitation.

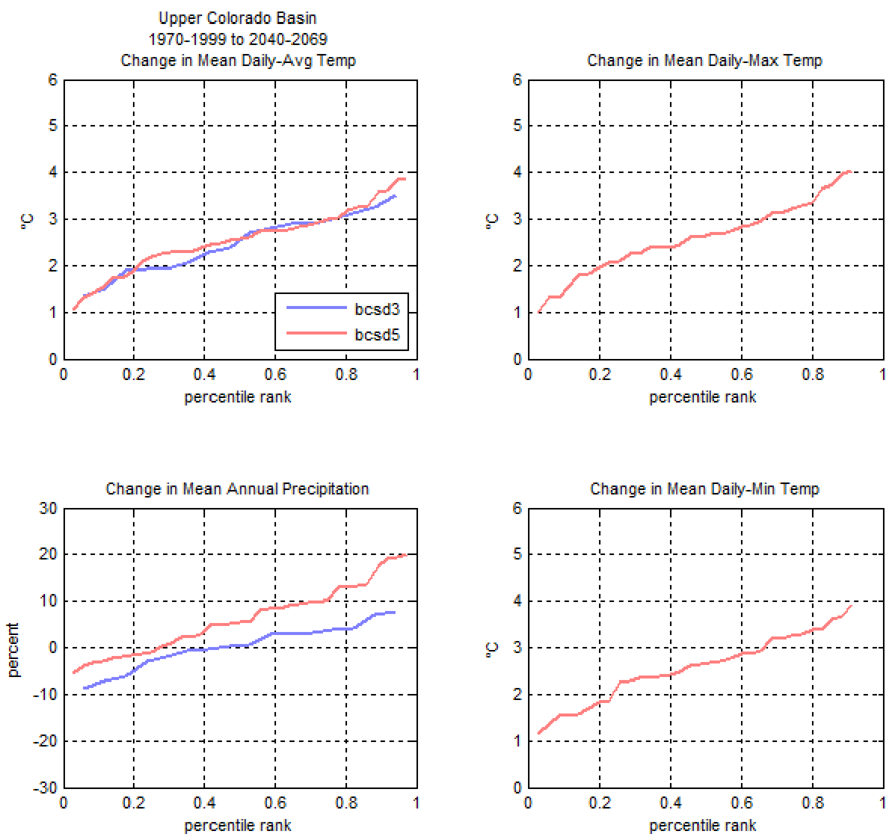

Figure 9. Distribution of changes in mean annual climate conditions integrated over the Upper Colorado Basin from 1970-1999 to 2040-2069 for BCSD3, BCSD5, and difference.

Each panel corresponds to a projected climate variable: precipitation, mean daily average temperature, mean daily minimum temperature, and mean daily maximum temperature. Each panel shows the distribution of model changes, computed through the three-step procedure summarized above. Note that BCSD5 scope included projections of all four variables, while BCSD3 scope addressed only precipitation and daily average temperature.

Does climate model balancing affect distribution differences?

The preceding evaluation was conducted again, but with the second step eliminated and the third step modified to identify the ensemble median of all projected changes, rather than model changes. In other words, the analysis was done with equally weighted projections and unequal model representation, rather than equalized model representation and unequal projection representation. Figure 10 shows that basin-scale changes are generally the same whether models are equally weighted (figure 9) or all simulations are counted equally. For example, the central tendency change, spread of change, and slope of change values from lesser to greater percentiles is about the same for the two approaches. The main difference between the distributions is that those based on equally weighted projections end up showing more extreme changes; the step (No. 2) of consolidating model changes tends to average out projection-specific extreme changes, which could be relevant to the communication of change uncertainty to some audiences. That being said, overall, the two approaches yield very similar distributions. For simplicity, the simpler approach of assuming equally weighted projections is carried forward in subsequent analyses.

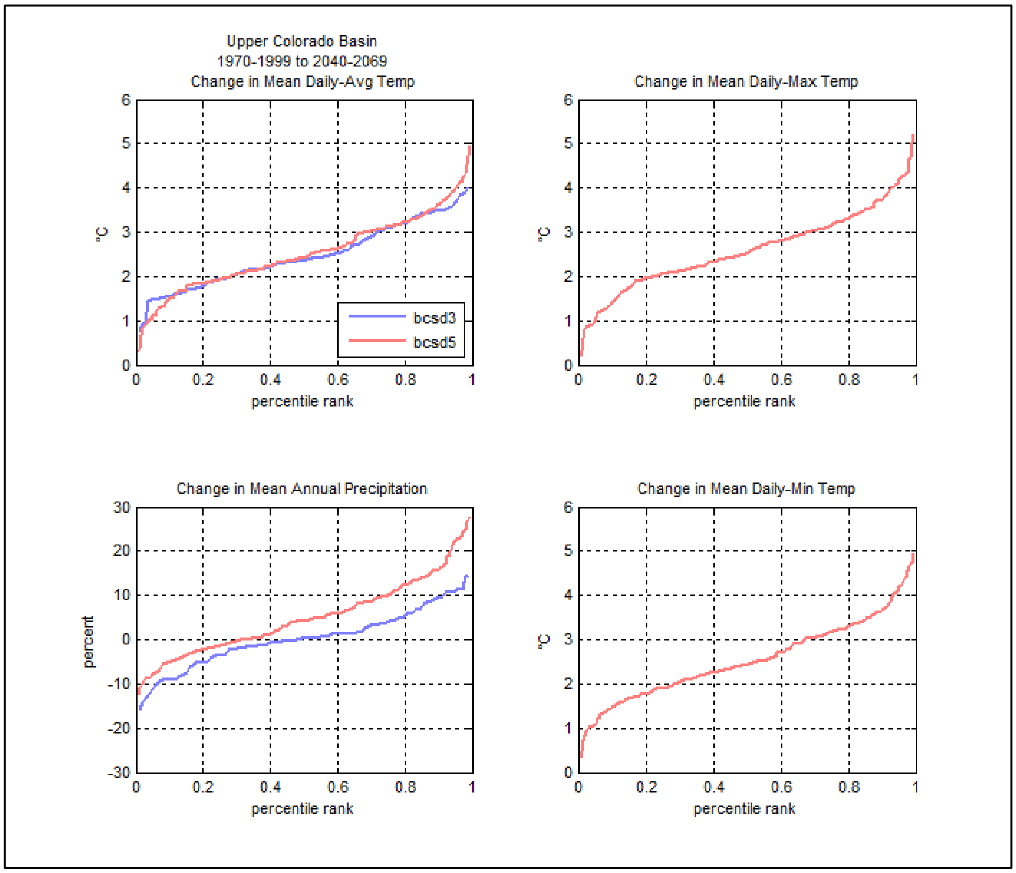

Figure 10. Same as figure 9 but with equally weighted projections rather than equally weighted model-specific groups of projections.

Do the two steps of BCSD affect results?

As discussed in section 3.1, for BCSD CMIP3 and BCSD CMIP5 applications, three separate ensembles were produced: REGRID, BC, and BCSD. Figure 11 shows basin-integrated precipitation and temperature change distributions for these three ensembles.

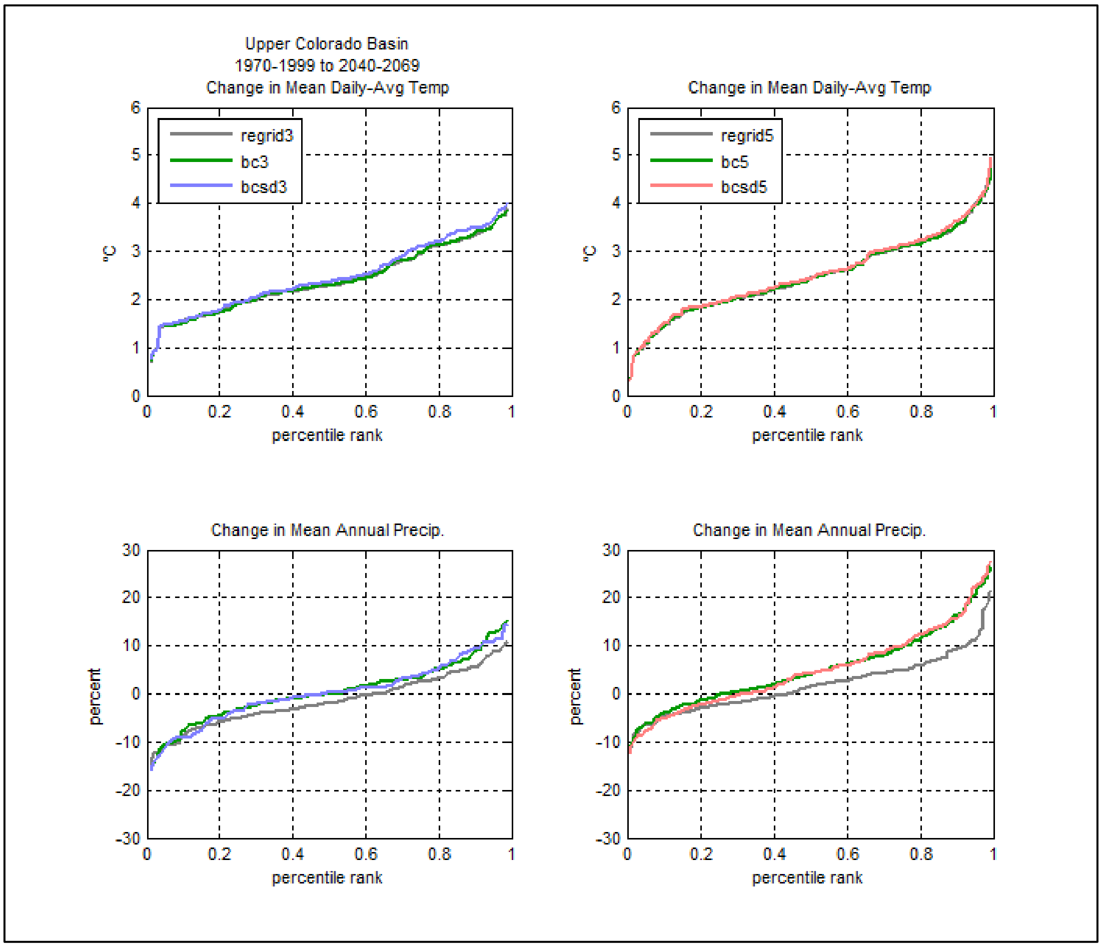

Figure 11. Same as figure 10 but focusing on precipitation and mean daily average temperature and showing results for REGRID, BC, and BCSD. Left column shows change distributions from CMIP3 for results prior to bias-correction (REGRID3), after bias-correction (BC3), and after spatial downscaling (BCSD3). Right column is similar, but for change distributions from CMIP5.

Focusing on temperature change distributions (top row of panels), it is evident that the REGRID and BC change distributions are similar to one another in both CMIP3 and CMIP5 applications (i.e., compare positions of gray and green lines). This is to be expected given that REGRID temperature trends are preserved during bias-correction (appendix A). It is also evident that spatial disaggregation does little to modulate basin-integrated change distributions (comparing BC and BCSD for both applications).

Focusing on precipitation, the effect of spatial disaggregation on basin-integrated change distribution is minor compared to the effect of bias-correction. Recall that the latter is performed without the constraint of preserving a projection's REGRID precipitation trend (appendix A). Consistent with previous reporting (Reclamation, 2011), comparison of figure 11 REGRID and BC precipitation changes shows that precipitation bias-correction generally leads to wetter changes (as discussed in section 3.1 in association with Figure 4). It appears that this effect is more pronounced in the CMIP5 application (also pointed out in the section 3.1 discussion). In addition, it is apparent from figure 11 that this wetting effect is more pronounced among the above-median change percentiles, where the REGRID changes tend to be precipitation increases in this basin.

- **User Need:** Understanding why the quantile-mapping bias-correction technique (appendix A) leads to a systematic wettening over the Upper Colorado Basin integrated annual precipitation changes, and why it is potentially more substantial when starting from relatively wet REGRID changes.

Does separation of results by emissions scenario affect results?

The question of "How are the climate change distributions similar and different by mid-21st century?" was revisited, but with CMIP3 and CMIP5 projected changes grouped by emissions scenario. Results are shown on figure 12 for temperature changes and on figure 13 for precipitation changes.

For temperature, one would expect temperature changes to be greater for the higher emissions scenarios; albeit we should point out that the effects of different GHG scenarios may still be somewhat overlapping by mid-century, especially for changes over smaller regions. One reason is that projected changes in global mean temperature are highly correlated with projected changes in temperature over the U.S. Another reason is that projected changes over the U.S. are, generally speaking, spatially smooth over large regions (e.g., figure 2, right column). Figure 12 is consistent with this expectation. The BCSD3 distributions show warming that is progressively larger from lower emissions (B1) to higher emissions (A2). A similar progression is seen in the BCSD5 distributions, tracking through RCPs 2.6, 4.5, and 8.5. RCP 6.0 includes a disproportionately smaller number of projections and represents fewer climate models, which may help explain why its changes do not exceed those of RCP 4.5.

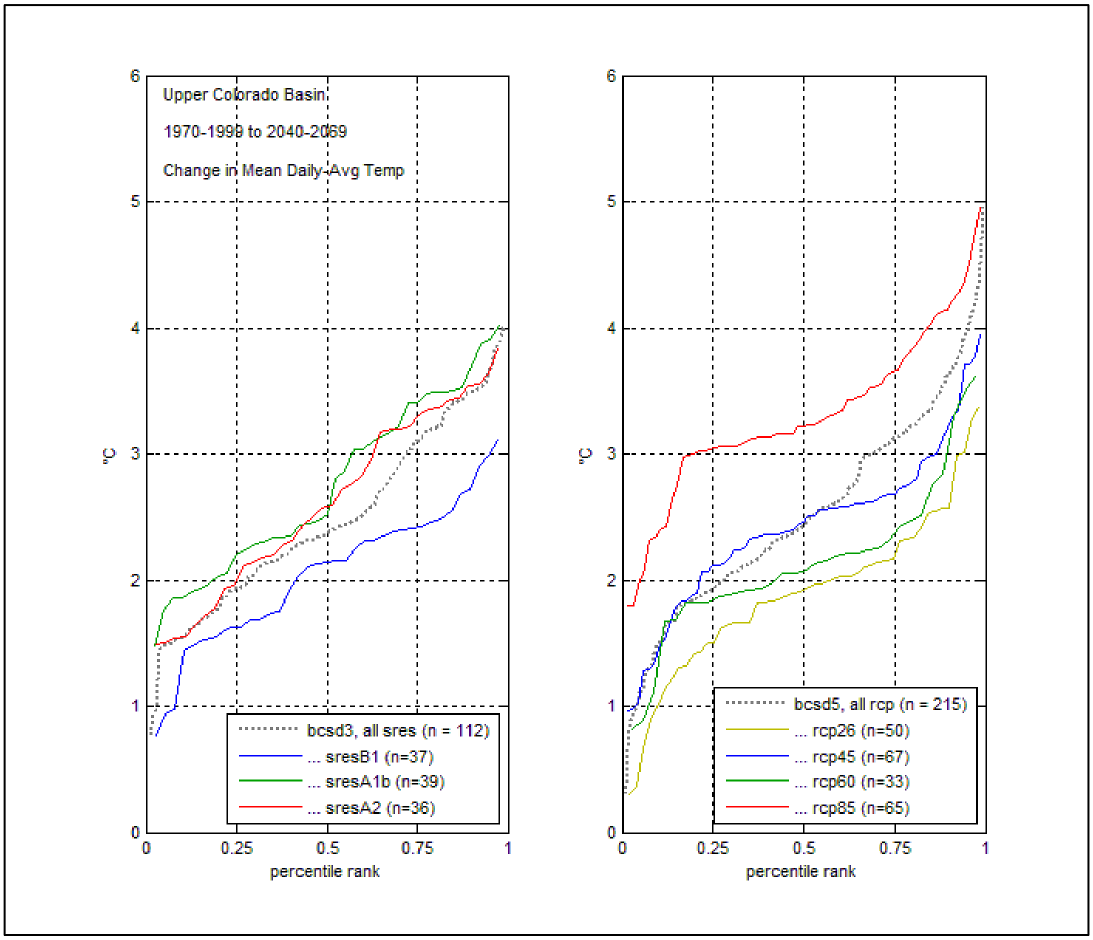

Figure 1. Same as Error! Reference source not found. **but focusing on mean-annual daily-average temperature and showing results by emissions scenario. Left panel shows BCSD3 change distributions for all projections pooled and by emission scenario (B1, A1b, and A2). Right panel shows BCSD5 change distributions for all projections pooled and by representative concentration pathway (RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5).**

For precipitation, we had no preconceived notion as to how the Upper Colorado Basin precipitation might shift with direct respect to the intensity of global GHG emissions. Figure 13 shows that there is no clear hierarchy of change distributions with respect to emissions intensity. However, it does show that there is some uncertainty in the change distributions spread and central tendency, which may simply be an artifact of considering different projection ensembles. Focusing on BCSD5 and RCP 6.0, the change distributions appear to depart from those of the other three RCPs. As mentioned above, the fact that the RCP 6.0 ensemble has fewer members and represents fewer models may be contributing to this result.

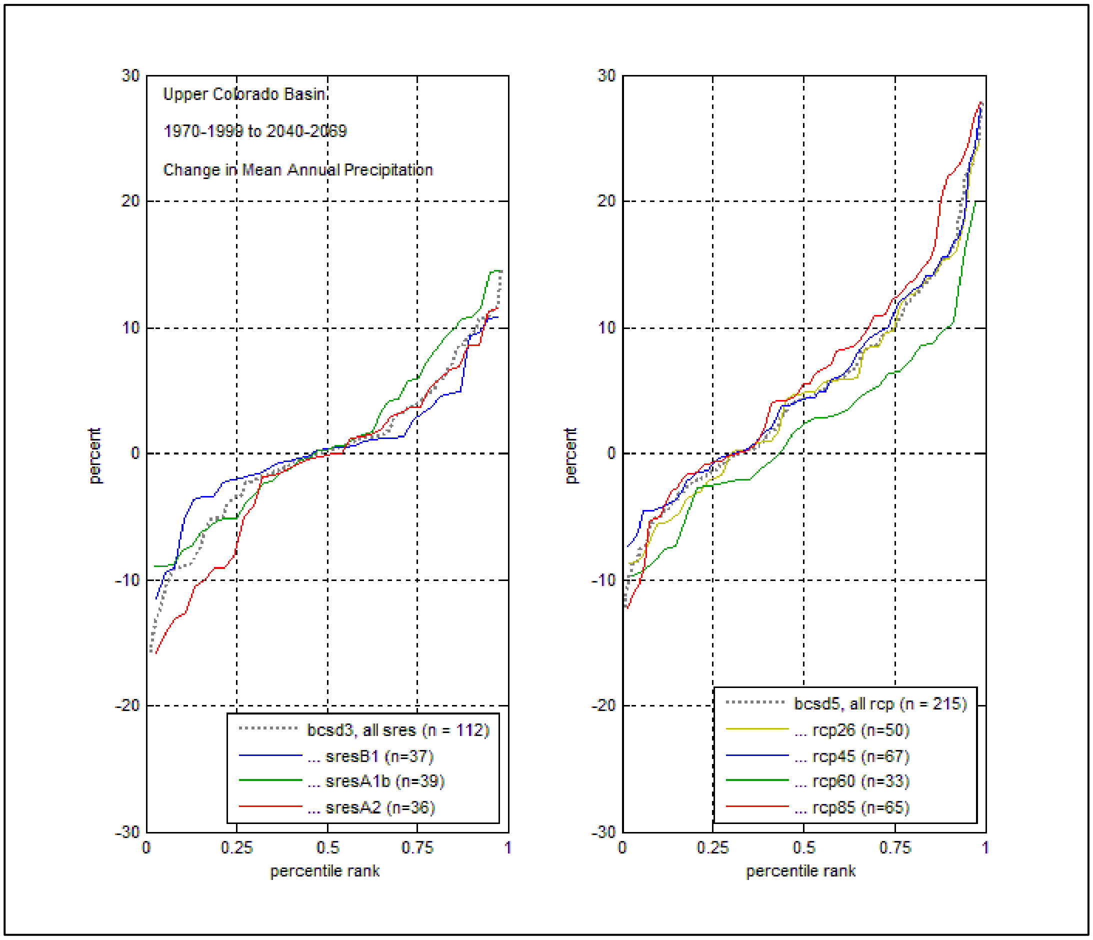

Figure 13. Same as figure 10 but focusing on mean annual precipitation and showing results by emissions scenario.

How are the central-tendency monthly climate changes similar and different by the mid-21st century?

All of the evaluations presented in sections 3.1 and 3.2 have focused on change in mean annual temperature and precipitation. Many water and environmental resource planning questions depend on projected changes in seasonal to monthly climate. Figure 14 illustrates median changes by calendar month for both variables, considering the BCSD3 and BCSD5 ensembles with projections equally weighted.

For temperature, it is apparent that while the ensemble-median change in mean annual temperature is about the same for BCSD3 and BCSD5 (figure 9), there are seasonal differences. During winter and spring months (November through April), BCSD5 projections express warmer conditions (~0.2 ºC). During summer months (June through August), the reverse is true, as BCSD5 is 0.2 to 0.4 ºC cooler.

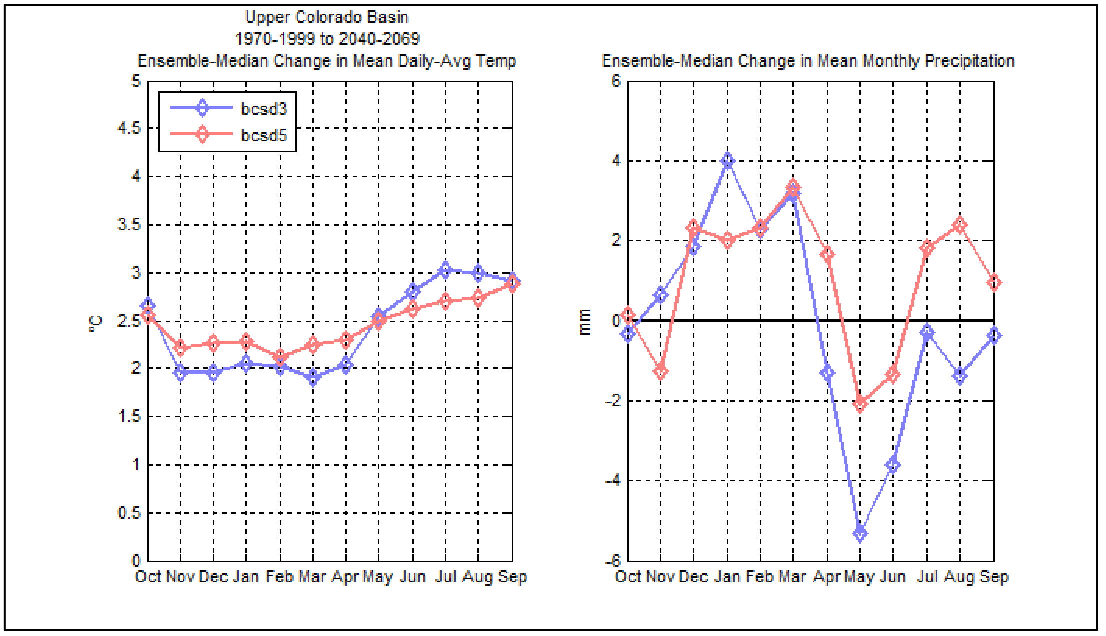

Figure 14. Change in basin-average mean-monthly climate in the Upper Colorado Basin, from 1970-1999 to 2040-2069.

For precipitation, the cool season changes are generally the same, although BCSD3 is wetter during November and February. What is perhaps more interesting is how, during April through September, BCSD5 is consistently wetter than BCSD3. This suggests that the key seasonal changes contributing to the increase in mean annual precipitation (figure 9) may be occurring primarily during spring and summer. This draws attention to research needs addressing key climatic controls on Colorado Basin precipitation during those seasons and the general weakness of current GCM representations of the North American Monsoon System.

- **User Need:** Understanding why CMIP5 projected changes in monthly climate differ from those in CMIP3, and how climate model simulation of season-specific mechanisms contributes to these differences.

3.3 Summary

The comparison of downscaled CMIP5 and CMIP3 climate projections over the Western U.S. shows broad regional similarities (e.g., similar levels of warming throughout much of the west and similar precipitation trends towards the north and towards the southwest). There are also notable differences for some regions (e.g., greater warming over the Upper Columbia Basin, less precipitation over the northern Great Plains, and more precipitation over California and the Upper Colorado Basin). Projections showing wetter portions of California and the

Upper Colorado are notable because they challenge the prevailing perspective of climate change impacts to the region that has been held since 2007 (informed by CMIP3); namely, that these regions will become drier and result in reduced runoff. It is important to recognize that while CMIP5 offers new information, more work is required to better understand CMIP5 and its differences from CMIP3, including:

- Understanding why CMIP5 projected changes in annual climate differ from those in CMIP3, and the extents to which these differences are attributable to changes in global climate model composition and/or use of different climate forcing emissions scenarios

- Understanding how the differences between downscaled CMIP5 and CMIP3 projections are sensitive to the choice of emissions scenario

- Understanding why CMIP5 projected changes in monthly climate differ from those in CMIP3, and how climate model simulation of season-specific mechanisms contributes to these differences

- Understanding why the quantile-mapping bias-correction scheme used in BCSD and BCCA resulted in wetter results in the CMIP5 application compared to the CMIP3 application, with potentially greater effect when starting from relatively wet REGRID changes (e.g., as found for the Upper Colorado River basin)

- Understanding the respective roles of quantile-mapping bias-correction and spatial disaggregation in modulating the intensity and spatial pattern of annual climate change from REGRID to BCSD projections

Once again, we note that this section provides only a cursory comparison of the CMIP5 and CMIP3 downscaling results. Users may wish to explore other questions as they seek to characterize and understand differences, including questions that explore how differences relate to climate model structures. Example questions:

1. To what extent do the precipitation results from the “old” climate models found in both CMIP3 and CMIP5 (i.e. coupled atmosphere-ocean general circulation models) compare to results from the relatively “new” models (i.e., earth system models, featuring carbon cycle dynamics interacting with coupled atmosphere-ocean circulation)?

2. How do precipitation results from the newer CMIP5 version of the 16 CMIP3 models differ from the results produced by the corresponding CMIP3 models?

3. To what extent do the precipitation results from the relatively finer spatial resolution CMIP5 models compare to results from the relatively coarser spatial resolution CMIP5 models?

4. Improving our Understanding of Downscaled CMIP5 Information

4.1 User Needs

The evaluation of section 3 addresses differences in CMIP5 and CMIP3 projections of annual to monthly climate variables and for a limited set of scales and statistics. The needs arising from that evaluation (section 3.3) fit within a broader outline of potential user interests surrounding the release of downscaled CMIP5 climate projections:

- **Characterizing the differences:** What are the differences among CMIP5 and CMIP3 portrayals of different hydroclimate variables (e.g., precipitation, temperature, runoff, evapotranspiration, etc.) at different space scales (e.g., hydrologic unit code 2-digit to 12-digit) and time scales (e.g., daily, seasonal, annual, multi-year)?

- **Explaining the differences:** How are these differences attributable to use of new global climate models, use of new climate forcing scenarios, chosen downscaling technique, and chosen hydrologic analysis methodology (for applicable variables)?

- **Relating to past decision Support:** How sensitive are the results from CMIP3-informed studies to these differences? What does this mean for decisions supported by those studies?

- **Relating to future decision support:** Which dataset should be used: (1) CMIP3 until CMIP5 is further evaluated and understood? (2) CMIP5 since it features latest advancements in climate modeling and estimation of future climate forcing? (3) pooled CMIP3 and CMIP5 unless rationale can be offered as to why one is more credible than the other? What CMIP5 information is reliable enough to support adaptation investments, and for what kinds of investment situations?

4.2 Research Centers and Activities

This section provides a snapshot of current research that could help us advance understanding of CMIP5 and how it differs from CMIP3. The purpose of this section is to give readers a sense of what type of research is occurring, and through what types of organizations. Readers are cautioned that this section does not present an exhaustive list of ongoing activities. Readers should also understand that the collection of research activities and participating research centers will continue to evolve in the years following release of CMIP5. With these cautions noted, this section offers some information about active research centers and ongoing efforts.

Research Centers

- **NOAA Modeling Applications, Prediction and Projections (MAPP) – CMIP5 Task Force:** The NOAA MAPP program's mission is to enhance the Nation's capability to understand and predict natural variability and changes in Earth's climate system. The program supports development of advanced climate modeling technologies to improve simulation of climate variability, prediction of future climate variations from weeks to decades, and projection of long-term future climate conditions. It also supports research focused on the coupling, integration, and application of Earth system models and analyses across NOAA, among partner agencies, and with the external research community. MAPP also facilitates interaction among its grant recipients through task forces on drought, CMIP5, and climate prediction. The CMIP5 Task Force brings together scientists whose MAPP-funded research in the framework of CMIP5 aims at evaluating simulations of the 20th-century climate and the uncertainties of long-term predictions and projection of 21st-century climate over North America. To learn more, visit: http://cpo.noaa.gov/ClimatePrograms/ModelingAnalysisPredictionsandProjections/MAPPTaskForces/CMIP5TaskForce.aspx.

- **NOAA Regional Integrated Science and Assessment (RISA) Centers:** NOAA's RISA program supports research teams that help expand and build the nation's capacity to prepare for and adapt to climate variability and change. RISA teams work with public and private user communities on several research fronts, including development of knowledge on impacts, vulnerabilities, and response options through interdisciplinary research and participatory processes. There are nine RISA centers located within the contiguous U.S. To learn more, visit: http://cpo.noaa.gov/ClimatePrograms/ClimateSocietalInteractionsCSI/RISAProgram/AboutRISA.aspx.

- **U.S. Department of the Interior Climate Science Centers (CSCs):** The mission of the CSCs is to deliver basic climate change impact science to Landscape Conservation Cooperatives (LCCs) within their respective regions, including physical and biological research, ecological forecasting, and multi-scale modeling. CSCs will prioritize their delivery of fundamental science, data and decision support activities to meet the needs of the LCCs. This includes working with the LCCs to provide climate change impact information on natural and cultural resources and to develop adaptive management and other decision support tools for managers. To learn more, visit: http://www.doi.gov/csc/index.cfm.

Example Research Activities

- California winter precipitation change under global warming in the CMIP5 ensemble:
  - Support: NOAA MAPP
  - Principal Investigator (PI): J. David Neelin, University of California, Los Angeles (UCLA)
  - Co-PI: Joyce E. Meyerson, Alex Hall, Neil Berg, UCLA
  - Summary: See Neelin et al. (2013) (revised), which explores how CMIP5 features greater agreement in projected winter precipitation change (December-February) than earlier phases of CMIP5. Findings suggest this greater agreement depends substantially on large-scale shifts in the storm tracks arriving at the coast. These shifts appear to be associated with an eastward extension of the region of strong Pacific Jetstream, which appears to be a robust feature of the CMIP5 large-scale simulated atmospheric circulation changes.
- Quantification and reduction of uncertainties in projections of climate impacts on drought and agriculture for North America:
  - Support: NOAA MAPP
  - PI: Justin Sheffield, Princeton University
  - Co-PI: David Lobell, Stanford University
  - Summary: Evaluate the uncertainties in estimates of future changes in climate, water availability, and agricultural production, and make improved estimates by incorporating state-of-the-art knowledge of the relationships between climate, hydrology, and agriculture into modeling and downscaling.
- Understanding the emerging central Pacific El Niño Southern Oscillation (ENSO) and its impacts on North American climate:
  - Support: NOAA MAPP
  - PI: Professor Jin-Yi Yu, University of California - Irvine

  - Summary: Data analyses and model experiments to better understand the evolution of the Central Pacific ENSO and its regional impacts on the Pacific-North America sector and to identify the key atmospheric and oceanic processes for differentiating the impacts of the Central Pacific and Eastern Pacific ENSO's on North American climate.

- Nonlinearity of the tropical convection and the asymmetry of the ENSO:
  - Support: NOAA MAPP
  - PI: Tao Zhang, NOAA/Earth System Research Laboratory (ESRL)
  - Co-PI: De-Zheng Sun, NOAA ESRL
  - Summary: Provide a better understanding of how the simulation of ENSO—the asymmetry between its two phases in particular—in global climate models is affected by increases in model resolution and changes in convection scheme, in support of the development of next-generation climate models involving both higher resolution and improved physical representations.

- Understanding and predicting tropical and North Atlantic sea surface temperatures (SST) forcing on variations in warm season precipitation over North America:
  - Support: NOAA MAPP
  - PI: Qi S. Hu, University of Nebraska - Lincoln
  - Co-PI: Robert Oglesby and S. Feng, University of Nebraska - Lincoln
  - Summary: Use diagnostic and modeling methods to decipher and understand physical processes/causal links that connect tropical and North Atlantic sea surface temperature (SST) variations associated with the Atlantic Multidecadal Oscillation (AMO) to changes in atmospheric circulation and warm season precipitation regimes for North America.

- Central U.S. abnormality in climate change and its response to global warming:
  - Support: NOAA MAPP
  - PI: Zaitao Pan, Saint Louis University
  - Co-PI: Timothy Eicher, Saint Louis, University
  - Summary: Diagnosing individual climate change feedbacks is expected to improve our understanding of climate dynamics and shed light on separating climate change into natural and anthropogenic components.

This project proposes feedback processes and examines their contribution to abnormal climate change in the central and eastern U.S., which experienced a cooling trend is past decades.

- Observational constraints, diagnosis, and physical pathways for precipitation and extreme event processes in next-generation global climate models:
  - Support: NOAA MAPP
  - PI: J. David Neelin, University of California - Los Angeles
  - Summary: Use and extend a set of measures developed from observations, on the scales that high-resolution global climate models are now reaching, to evaluate a targeted set of processes in current climate models, specifically: (1) onset of deep convection, its water vapor-temperature dependence, and relation to entrainment assumptions; (2) excursions to high water vapor and strong precipitation regime; (3) quantification of similar long-tail behavior for surface temperature probability distributions; and (4) interactions at the margins of convective zones where the inflow air mass transported into a convective region is modified along its trajectory until conditions for convective onset are reached.

- Changes in intraseasonal to interannual variability of the Pan American monsoons under a warmer climate and their impacts on extreme events assessed by the CMIP5 models and observations:
  - Support: NOAA MAPP
  - PI: Rong Fu, The University of Texas - Austin
  - Co-PI: Kingste Mo, National Centers for Environmental Protection/National Weather Service/National Oceanic and Atmospheric Administration; and Weiqin Han, University of Colorado
  - Summary: Characterize the changes of intraseasonal, seasonal, and interannual variability and their impact on extreme events over the Pan America monsoon region as simulated and projected by the CMIP5 and NOAA Climate Forecast System models.

- An integrated view of the American monsoon systems: observations, models, and probabilistic forecasts:
  - Support: NOAA MAPP
  - PI: Leila M.V. Carvalho, University of California - Santa Barbara
  - Co-PI: Charles Jones, University of California - Santa Barbara

    - Summary: Develop a unified view of the Americas Monsoon Systems and evaluate the ability of global models from the WCRP CMIP3 and CMIP5 to simulate the variability of the AMS in the present climate

- In-depth regional process--level analyses of North American Regional Climate Change Assessment Program and Fifth Assessment Report simulations over North America: towards establishing differential credibility of regional climate projections
    - Support: NOAA MAPP
    - PI: Anji Seth, University of Connecticut, and Linda Mearns, National Center for Atmospheric Research (NCAR)
    - Co-PI: Melissa Bukovsky and David Gochis, NCAR
    - Summary: Develop a consistent set of process-oriented model analyses and apply them in different climate regimes in order to help define credible model members whose future simulated climates will have value for regional climate change assessment. Focus on warm-season precipitation in three regions.

- Natural climate variability and teleconnections to precipitation over the Pacific-North American region in CMIP3 and CMIP5 models:
    - Support: NOAA RISA
    - PI: Suraj D. Polade, Scripps Institution of Oceanography
    - Co-PI: Alexander Gershunov, Daniel R. Cayan, Michael D. Dettinger, and David W. Pierce, Scripps Institution of Oceanography.
    - Summary: The performance of 14 models with simulations in both the CMIP3 and CMIP5 archives is assessed using singular value decomposition analysis of simulated and observed winter Pacific SSTs and concurrent precipitation over the contiguous U.S. and northwestern Mexico. Results indicate that the CMIP5 generation of global climate models shows significant improvements in simulations of key Pacific climate modes and their teleconnections to North America compared to earlier CMIP3 simulations.

- Integrated scenarios of the future environment:
    - Support: U.S. Department of the Interior Northwest Climate Science Center (NW CSC), NOAA RISA Climate Impacts Research Consortium
    - PI: Philip Mote, Oregon State University, NW CSC, and NOAA RISA Climate Impacts Research Consortium

  - Summary: Develop optimal delivery of future integrated scenarios for climate, hydrology, and vegetation, addressing four obstacles (with primary focus on the first two): (1) limited guidance on selection of climate projections to inform scenarios; (2) limited demonstration in joint analysis of hydrology and vegetation response to climate change; (3) limited schemes that leverage higher-resolution regional climate modeling efforts; and (4) limited approaches that characterize and attribute sources of uncertainty.

- Next generation climate scenarios for use in the Climate Change Working Group, Sovereign Technical Team, Columbia River Treaty:
  - Support: NW CSC, NOAA RISA Climate Impacts Research Consortium
  - PI: Philip Mote, Oregon State University, NW CSC, and NOAA RISA Climate Impacts Research Consortium
  - Summary: Compare new CMIP5 projections for the Columbia Basin with a subset of CMIP3 projections.

- Downscaling CMIP3 and CMIP5 using multivariate adaptive constructed analogs
  - Support: NW CSC
  - PI: John Abatzaglou, University of Idaho, NW CSC
  - Focus: Develop archive of daily downscaled CMIP5 climate projections over the Western U.S. using a technique similar to BCCA, but including additional features well-tailored for evaluating wildland fire risk under climate change.

The CSCs and their administrative leads at the National Climate Change and Wildlife Science Center are also investing in downscaling research and in the Downscaled Geo Data Portal (GDP), which provides online access to multiple downscaled datasets. Their early efforts include developing additional data services stemming from the BCSD3 content described in this memorandum, with current efforts focusing on how to apply such data services to BCCA3, BCSD5, and BCCA5 content. To learn more about which complements information described in this memorandum. To learn more about the GDP effort, visit: (http://cida.usgs.gov/climate/gdp/).

5. References

Brekke, LD., and J.J. Barsugli, 2012. Chapter 11 – "Uncertainties in Projections of Future Changes in Extremes," *Extremes in a Changing Climate - Detection, Analysis and Uncertainty*. A. AghaKouchak et al. (eds.), Water Science and Technology Library 65, DOI 10.1007/978-94-0007-4479-0, Springer, 423 p.

Collins, W.D., C.M. Bitz, M.L. Blackmon, G.B. Bonan, C.S. Bretherton, J.A. Carton, P. Chang, S.C. Doney, J.J. Hack, T.B. Henderson, J.T. Kiehl, W.G. Large, D.S. McKenna, B.D. Santer, and R.D. Smith, 2006. "The Community Climate System Model Version 3 (CCSM3)," *J. Climate,* 19(11):2122-2143.

Delworth, T.L. et al, 2005. "GFDL's CM2 Global Coupled Climate Models Part 1: Formulation and Simulation Characteristics," *J. Climate,* 19:643-674.

Deser, C., A. Phillips, V. Bourdette, and H. Teng, 2010. "Uncertainty in Climate Change Projections: the Role of Internal Variability," *Clim. Dyn.,* DOI 10.1007/s00382-010-0977-x.

Diansky, N.A., and E.M. Volodin, 2002. "Simulation of Present-Day Climate with a Coupled Atmosphere-Ocean General Circulation Model," *Izv. Atmos. Ocean Phys.* (Engl Transl), 38(6):732-747.

Flato, G.M., and G.J. Boer, 2001. "Warming Asymmetry in Climate Change Simulations," *Geophys. Res. Lett*., 28:195-198.

Fowler, H. J., S. Blenkinsop, and C. Tebaldi, 2007. "Linking Climate Change Modelling to Impact Studies: Recent Advances in Downscaling Techniques for Hydrological Modelling," *Int. J. Climatol*., 27, 1547-1578.

Furevik, T., M. Bentsen, H. Drange, I.K.T. Kindem, N.G. Kvamstø, and A. Sorteberg, 2003. Description and Evaluation of the Bergen Climate Model: ARPEGE Coupled with MICOM," *Clim. Dyn.,* 21:27-51.

Gordon C., C. Cooper, C.A. Senior, H.T. Banks, J.M. Gregory, T.C. Johns, J.F.B. Mitchell, and R.A. Wood, 2000. "The Simulation of SST, Sea Ice Extents and Ocean Heat Transports in a Version of the Hadley Centre Coupled Model Without Flux Adjustments," *Clim. Dyn.,* 16:147-168.

Gordon, H.B., L.D. Rotstayn, J.L. McGregor, M.R. Dix, E.A. Kowalczyk, S.P. O'Farrell, L.J. Waterman, A.C. Hirst, S.G. Wilson, M.A. Collier, I.G. Watterson, and T.I. Elliott, 2002. *The CSIRO Mk3 Climate System Model.* CSIRO Atmospheric Research Technical Paper No. 60, CSIRO Division of Atmospheric Research, Victoria, Australia, 130 p.

Hawkins, E., and R.T. Sutton, 2009. "The Potential to Narrow Uncertainty in Regional Climate Predictions," *Bulletin of the American Meteorological Society*, 90(8), pp. 1095-1107.

Hawkins, E., and R.T. Sutton, 2010. "The Potential to Narrow Uncertainty in Projections of Regional Precipitation Change," *Climate Dynamics*, DOI: 10.1007/s00382-010-0810-6.

Hidalgo, H.G., M.D. Dettinger, and D.R. Cayan, 2008. *Downscaling with Constructed Analogues: Daily Precipitation and Temperature Fields over the United States.* California Energy Commission, Public Interest Energy Research Program, Sacramento, California, 62 p.

IPCC, 2000. *Emissions Scenarios.* Special Report of the Intergovernmental Panel on Climate Change, Nebojsa Nakicenovic and Rob Swart (eds.), Cambridge University Press, Cambridge, United Kingdom, and New York, New York, USA, 570 p.

IPSL, 2005. *The New IPSL Climate System Model: IPSL-CM4.* Institut Pierre Simon Laplace des Sciences de l'Environnement Global, Paris, France, p. 73.

Jungclaus J.H., M. Botzet, H. Haak, N. Keenlyside, J-J Luo, M. Latif, J. Marotzke, U. Mikolajewicz, and E. Roeckner, 2006. "Ocean Circulation and Tropical Variability in the AOGCM ECHAM5/MPI-OM," *J. Climate,* 19:3952-3972.

K-1 Model Developers, 2004. *K-1 Coupled Model (MIROC) Description*. K-1 Technical Report, Hasumi, H., and S. Emori (eds.), Center for Climate System Research, University of Tokyo, 34 p.

Knutti R., and J. Sedláček, 2012. "Robustness and Uncertainties in the New CMIP5 Climate Model Projections," *Nature Climate Change*, doi:10.1038/nclimate1716.

Legutke, S., and R. Voss, 1999. *The Hamburg Atmosphere-Ocean Coupled Circulation Model ECHO-G.* Technical Report No. 18, German Climate Computer Centre (DKRZ), Hamburg, 62 p.

Maurer, E.P., L. Brekke, T. Pruitt, and P.B. Duffy, 2007. "Fine-Resolution Climate Projections Enhance Regional Climate Change Impact Studies," *Eos Trans. AGU*, 88(47), 504.

Maurer, E.P., H.G. Hidalgo, T. Das, M.D. Dettinger, and D.R. Cayan, 2010. "The Utility of Daily Large-Scale Climate Data in the Assessment of Climate Change Impacts on Daily Streamflow in California," *Hydrology and Earth System Sciences*, 14, 1125-1138, doi:10.5194/hess-14-1125-2010.

Meehl, G.A., C. Covey, T. Delworth, M. Latif, B. Mcavaney, J.F.B. Mitchell, R.J. Stouffer, and K.E. Taylor, 2007. "The WCRP CMIP3 Multimodel Dataset – A New Era in Climate Change Research," *Bulletin of the American Meteorological Society*, 88(9), 1383-1394.

Mote, P., L. Brekke, P.B. Duffy, and E. Maurer, 2011. "Guidelines for Constructing Climate Scenarios," *Eos Transactions*, 92(31), 257-258.

Neelin, J.D., B. Langenbrunner, J.E. Meyerson, A. Hall, and N. Berg, 2013. "California Winter Precipitation Change Under Global Warming in the Coupled Model Intercomparison Project 5 Ensemble," submitted to *J. Climate* (in review).

Pierce, D.W., T.P. Barnett, B.D. Santer, and P.J. Gleckler, 2009. "Selecting Global Climate Models for Regional Climate Change Studies," *Proc. National Academy Sciences*, 106 (21), 8441-8446.

Reclamation, 2011. *West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Surface Water Projections.* Technical Memorandum No. 86-68210-2011-01, U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Denver, Colorado, 138 p.

Russell, G.L., J.R. Miller, D. Rind, R.A. Ruedy, G.A. Schmidt, and S. Sheth, 2000. "Comparison of Model and Observed Regional Temperature Changes During the Past 40 Years," *J Geophys Res*., 105:14891-14898.

Salas-Mélia D., F. Chauvin, M. Déqué, H. Douville, J.F. Gueremy, P. Marquet, S. Planton, J.F. Royer, and S. Tyteca, 2005. "Description and Validation of the CNRM-CM3 Global Coupled Model," submitted to *Clim. Dyn*. (in review).

Taylor, K.E., R.J. Stouffer, and G.A. Meehl, 2011. *A Summary of the CMIP5 Experiment Design*. January 22, 2011, 33 p., available at: http://cmip-pcmdi.llnl.gov/cmip5/docs/Taylor_CMIP5_design.pdf.

van Vuuren, D.P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G.C. Hurtt, T. Kram, V. Krey, J-F Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S.J. Smith, and S.K. Rose, 2011. "The Representative Concentration Pathways: An Overview," *Climatic Change*, 109:5-31.

Washington W.M., J.W. Weatherly, G.A. Meehl, A.J. Semtner, T.W. Bettge, A.P. Craig, W.G. Strand, J. Arblaster, V.B. Wayland, R. James, and Y. Zhang, 2000. "Parallel Climate Model (PCM) Control and Transient Simulations," *Clim. Dyn*., 16:755-774.

Wood, A.W., E.P. Maurer, A. Kumar, and D.P. Lettenmaier, 2002. "Long-Range Experimental Hydrologic Forecasting for the Eastern United States," *J. Geophysical Research-Atmospheres*, 107(D20), 4429.

Wood, A.W., L.R. Leung, V. Sridhar, and D.P. Lettenmaier, 2004. "Hydrologic Implications of Dynamical and Statistical Approaches to Downscaling Climate Model Outputs*,"* *Climatic Change*, 15(62):189-216.

Yukimoto S., A. Noda, A. Kitoh, M. Sugi, Y. Kitamura, M. Hosaka, K. Shibata, S. Maeda, and T. Uchiyama, 2001. "The New Meteorological Research Institute oupled GCM (MRI-CGCM2) -- model climate and variability. *Pap Meteorol Geophys* 51:47-88.

Appendix A

Climate Projection Downscaling Methods

Table of Contents

Figures

Appendix A

Climate Projection Downscaling Methods

A.1 Monthly Bias Correction Spatial Disaggregation (BCSD)

This procedure was introduced in Wood et al. 2002, Wood et al. 2004, and Maurer 2007, and involves using the following two-step procedure discussed below.

BCSD Step 1. Bias-Correction

When comparing historical simulation results from global climate models (GCM) to observations, comparison often shows that simulations tend to be biased wet, dry, cool, and/or warm, with biases varying by location, season, and variable. The purpose of this step is to identify such bias and then remove it from the projection datasets.

The approach is a quantile mapping technique operated on a monthly and location-specific basis as outlined below. To enable efficient application of the methodology to many global climate projections having diverse spatial resolutions, the global climate simulation outputs are first regridded to a common coarse grid (i.e. "REGRID" resolution, which is 2 degrees [°] in the BCSD Coupled Model Intercomparison Project phase 3 [CMIP3] application and 1° in the BCSD Coupled Model Intercomparison Project phase 5 [CMIP5] application). Also, a targeted, spatially finer resolution is adopted at the start (i.e., "downscaled" resolution, which is 1/8° in the case of both applications).

1.1 **Gather Data:** Start with three datasets: (1) observed historical data (OBS) describing 20th century surface climate conditions specified at the downscaled resolution; (2) simulated historical conditions from a given GCM's simulation of 20th century climate specified at the REGRID resolution; and (3) the GCM's simulated future climate conditions initialized by the end climate states from (2), also specified at the REGRID resolution. For (1), data from Maurer et al. (2002)[1] were used. A corresponding coarsened version of these data was developed at the REGRID resolution, spatially interpolated from the downscaled resolution. The coarsened version guides the bias-correction technique and also the subsequent spatial downscaling technique. On (2) and (3), users may access online information describing how historical climate

[1] http://www.engr.scu.edu/~emaurer/data.shtml#Gridded_Obs.

simulations correspond to future climate projections.[2] For the BCSD CMIP3 application, this step involves gathering data for two variables in each of the three datasets: monthly precipitation (P) and mean daily-average surface air temperature (Tavg). For the BCSD CMIP5 application, the data for four variables are gathered: the two prior variables plus daily-minimum (Tmin) and daily-maximum (Tmax) surface air temperatures.

1.2 **Identify Bias:** The bias-correction basis is identified by focusing on datasets (1) and (2). This basis is then used to guide bias-correction of datasets (2) and (3). Identifying this basis requires adopting a bias-identification period of common overlap in datasets (1) and (2). In both BCSD CMIP3 and CMIP5 applications, this period was chosen to be 1950-1999. Consequently, the early 20th century portion of the GCM's 20^{th}-century simulation is trimmed so that a 1950-1999 time series, comparable to OBS, is retained. Bias-identification proceeds on a variable-, month- and location-specific basis, where location is a given REGRID-resolution grid cell. For values in that grid cell, month, and variable, construct cumulative distribution functions (CDFs) of conditions from dataset (2) (i.e., GCM) and conditions from coarsened OBS. The paired CDFs combine to form a "quantile map," where at each rank probability, or percentile, one can assess the bias between GCM and OBS (at that location, for that variable, and during that month). Repeat this procedure for all projections, producing a quantile map for every projection; note that the number of unique quantile maps equals the number of unique historical simulations initializing the future projections, which is typically fewer than the number of future projections because one historical simulation can initialize multiple future projections. An example ensemble of quantile maps for all calendar months at one REGRID-resolution grid cell in the BCSD CMIP3 application is shown on figure A1 and figure A2 for temperature and precipitation, respectively. In both figures, the heavy black line is the OBS CDF, and the ensemble of red lines contains the multiple GCM CDFs. The dashed green line overlies the black line and is a product of the next step (adjusted GCM CDFs, all sitting on top of one another).

1.3 **Correct Bias:** Adjust values of both datasets (2) and (3), using the quantile maps produced in step 1.2. The adjustment procedure is illustrated on figure A3. Proceed on a location- and timestep-specific basis, first moving sequentially through dataset (2) and then through

[2] For CMIP3, see http://www-pcmdi.llnl.gov/ipcc/time_correspondence_summary.htm. For CMIP5, such correspondence is indicated by X from a given CMIP5 projection's rXi1p1 identifier, defined at: http://cmip-pcmdi.llnl.gov/cmip5/docs/cmip5_data_reference_syntax_v0-25_clean.pdf.

dataset (3). At any timestep, the adjustment involves identifying the GCM value at that timestep, looking up the associated rank probability (p) from the GCM's historical "quantile map" (step 1.2), identifying the corresponding OBS value at this rank probability in the "quantile map," and then accepting that OBS value as the adjusted GCM value. This means that all adjusted GCM projections have monthly CDFs during the bias-identification period (step 1.2) that match the corresponding monthly OBS CDFs (i.e., illustrated as dashed green lines on figure A1 and figure A2, where one sees only one dashed green line on each panel, but there are, in fact, the same count of green lines as red lines, and the green lines happen to all sit on top of one another).

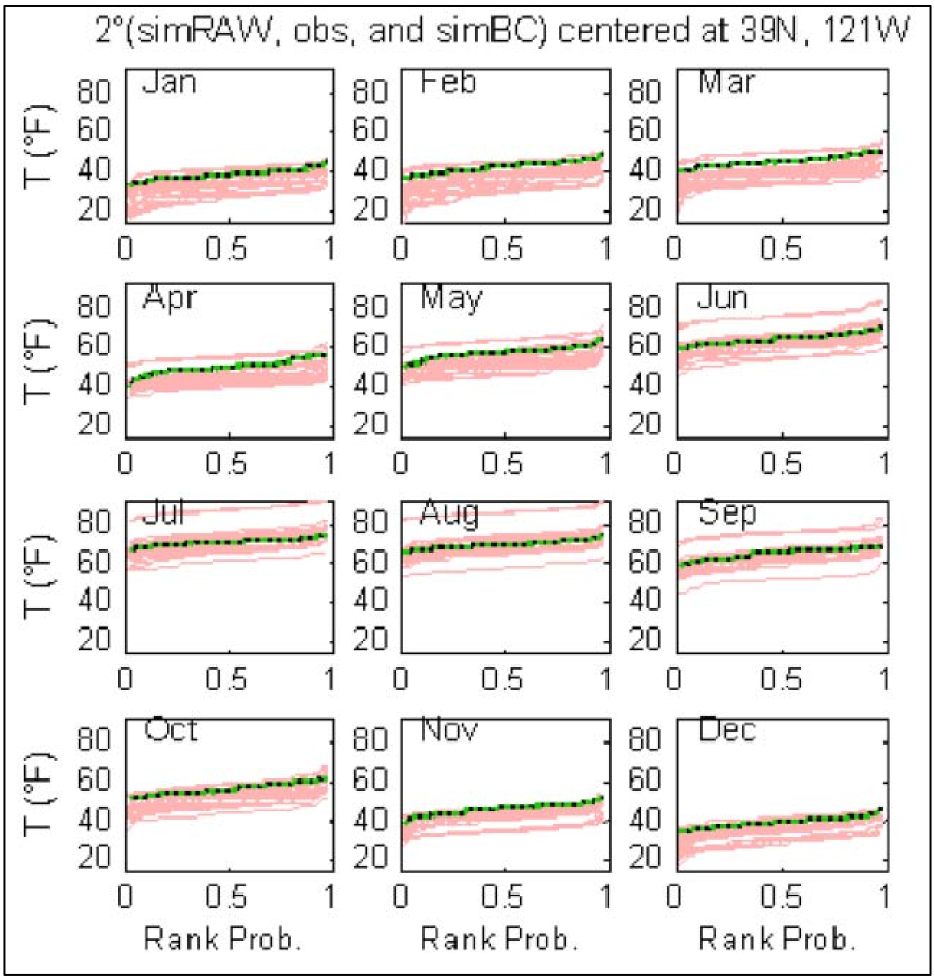

Figure A1. Examples of temperature quantile maps.

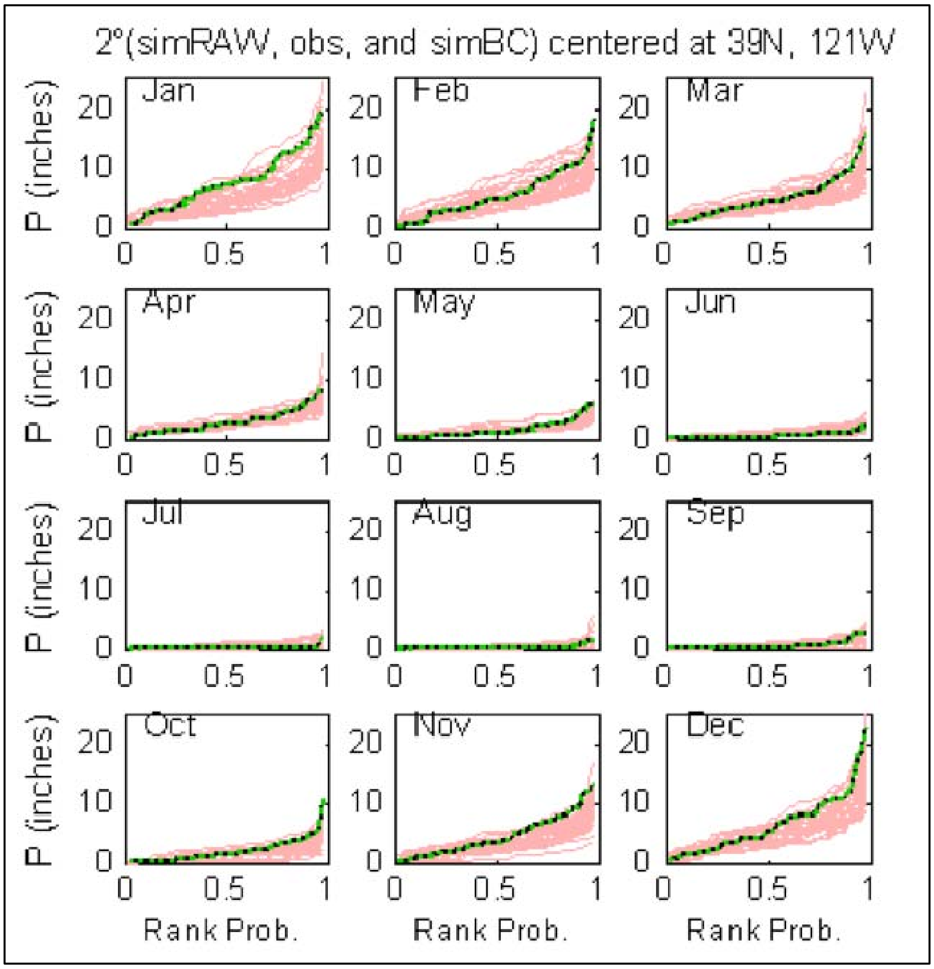

Figure A2. Examples of precipitation quantile maps.

The result of bias-correction is an adjusted GCM dataset (20th century and 21st century, linked together, or concatenated) that is statistically consistent with OBS during the bias-correction overlap period (i.e., 1950-1999 in this application)[3]. Beyond the bias-correction period, adjusted GCM reflects the same relative changes in mean, variance, and other statistical moments as projected by the GCM between the unadjusted GCM's 20th-century and 21st-century simulations, but mapped onto OBS variance.

[3] Also referred to as the bias-corrected, or BC, projection.

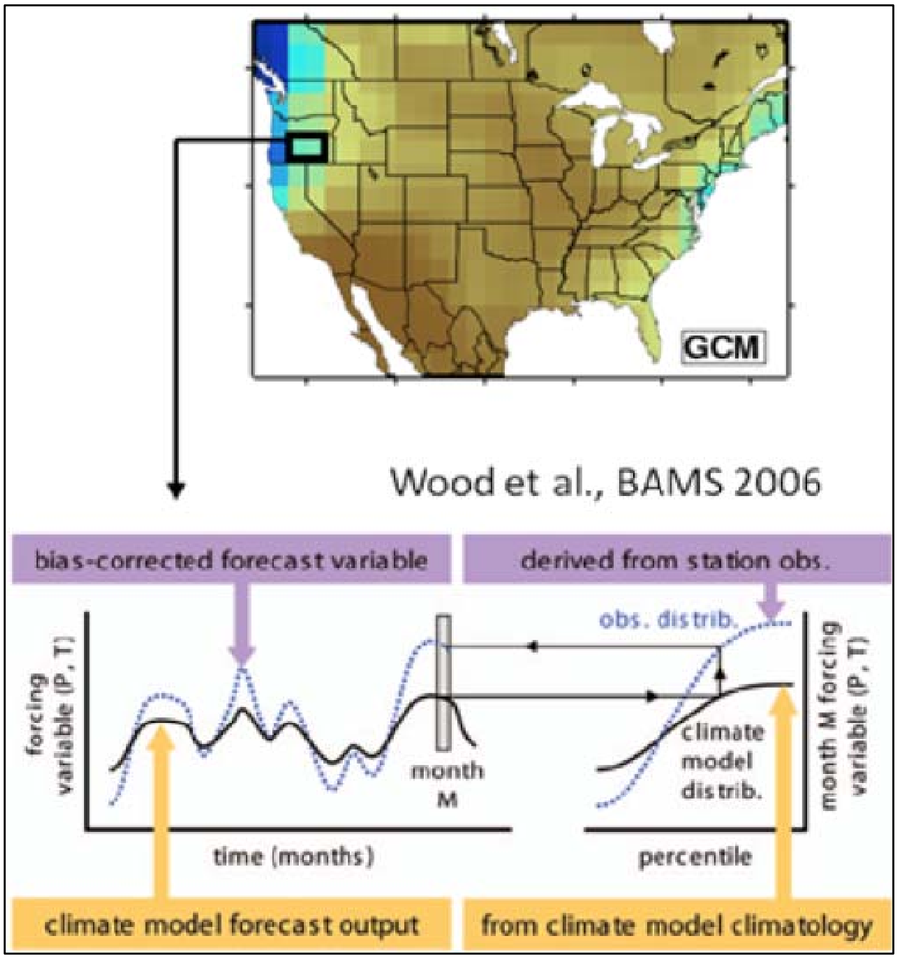

Figure A3. Applying quantile map to adjust simulated climate data.

Notes:

- This methodology assumes that the GCM biases have the same structure during the 20th- and 21st-century simulations.

- Before applying bias-correction to 21st-century Tavg, Tmin, and Tmax projections, the 21st-century GCM trend is removed, and then bias-correction is applied to the residual magnitudes to create adjusted GCM. Afterwards, the trend is added back to adjusted GCM (Maurer, 2007). As discussed by Wood et al. (2004), this is important during the temperature bias-correction step to prevent rising future temperatures from falling disproportionately on the extreme tail of the OBS CDF (which, as in section 1.2 above, was developed using 1950-1999 monthly temperatures).

- When applying bias-correction to 21st-century P projections, there is no trend removal prior to bias-correction. As a result, the "raw" (i.e., biased) and bias-corrected P projections are not constrained to have the same trend (unlike the Tavg, Tmin, and Tmax projections). Given that projected variance may differ from historical, this can cause raw and bias-corrected trends to differ (Pierce et al., 2013). In fact, it has been demonstrated that the process of bias-correcting P projections in this archive, without trend removal and reinsertion, leads to projected P trends that are slightly wetter after bias-correction for much of the contiguous U.S.

BCSD Step 2. Spatial Disaggregation

This step spatially translates adjusted GCM projections from the coarse REGRID and bias-correction resolution of step 1 to the targeted downscaled resolution. The procedure is performed on a timestep-specific basis for the full spatial domain and essentially involves merger of historical spatial climatology with the spatially disaggregated changes of the given timestep measured from that climatology.

1.1 **Adopt Spatial Climatology:** Start with the dataset (1) in step 1 and adopt a spatial climatology pattern that will be used to guide spatial disaggregation of changes. For both BCSD CMIP3 and BCSD CMIP5 applications, the 1950-1999 monthly mean spatial condition was adopted as this spatial climatology for a given variable. Initially proceed with the coarsened version of dataset (1) (i.e., 2° OBS in the BCSD CMIP3 application and 1° in the BCSD CMIP5 application). As an example, consider the BCSD CMIP3 application and the January spatial climatology for precipitation (figure A4).

1.2 **Compute Simulation Timestep Results Departure from Spatial Climatology:** Consider a single timestep solution of a given adjusted GCM projection variable at REGRID resolution (e.g., January 2040 of the bias-corrected CMIP3 P projection from the “miub echo g” climate model, simulating SRES A2, from initial condition No. 2 [run 2]). Compute factor values at every REGRID-resolution grid cell that reflects departure from the spatial climatology (OBS) at that grid cell. When the variable is P, compute the factor values as ratios of adjusted GCM to OBS. When the variables are Tmin, Tmax, or Tavg, compute the factor values as the difference of adjusted GCM minus OBS. Revisiting our example, this procedure is done for every REGRID-resolution grid-cell in our domain (figure A5), where factor values greater than one indicate January 2040 adjusted GCM values are wetter than OBS climatological January conditions.

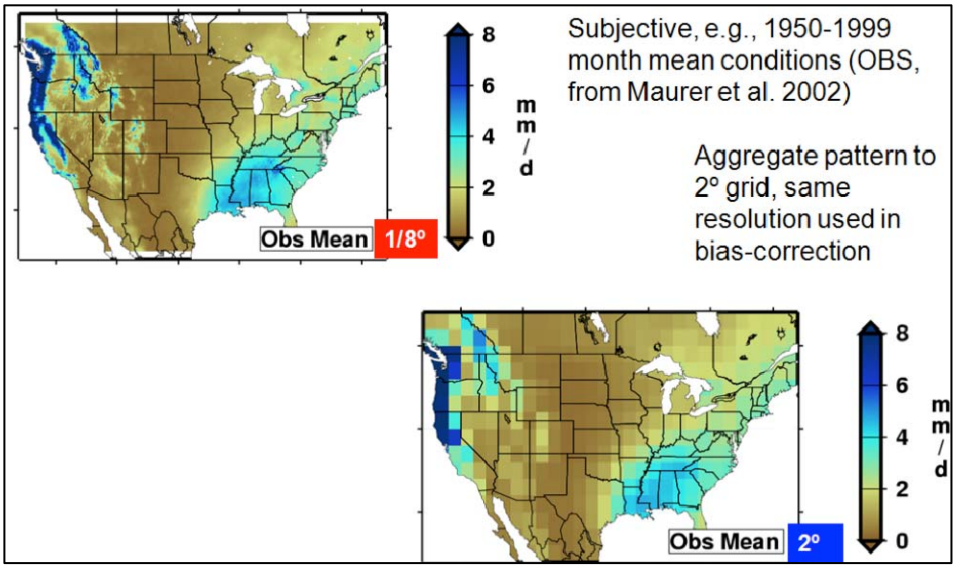

Figure A4. Spatial climatology to guide spatial downscaling showing January precipitation as an example.

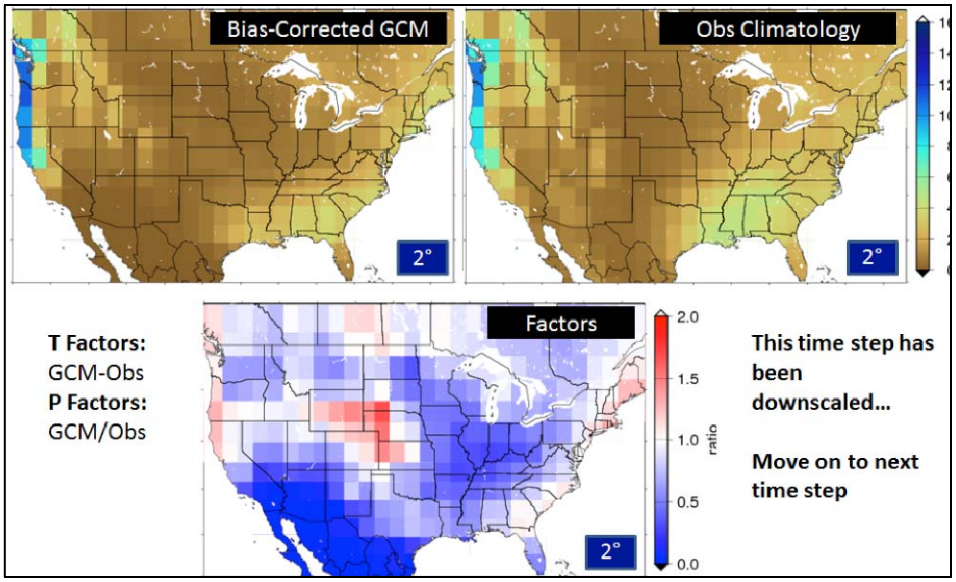

Figure A5. Computation of change factors at coarse resolution relative to spatial climatology, showing example for a single January month from an example climate projection.

1.3 **Interpolate Factor Values to Finer Resolution:** This step simply involves translating the coarse-resolution factor values to the targeted downscaled resolution (figure A6). This is done using the SYMAP algorithm (Shepard, 1984), which is basically a modified inverse-distance-squared interpolation.

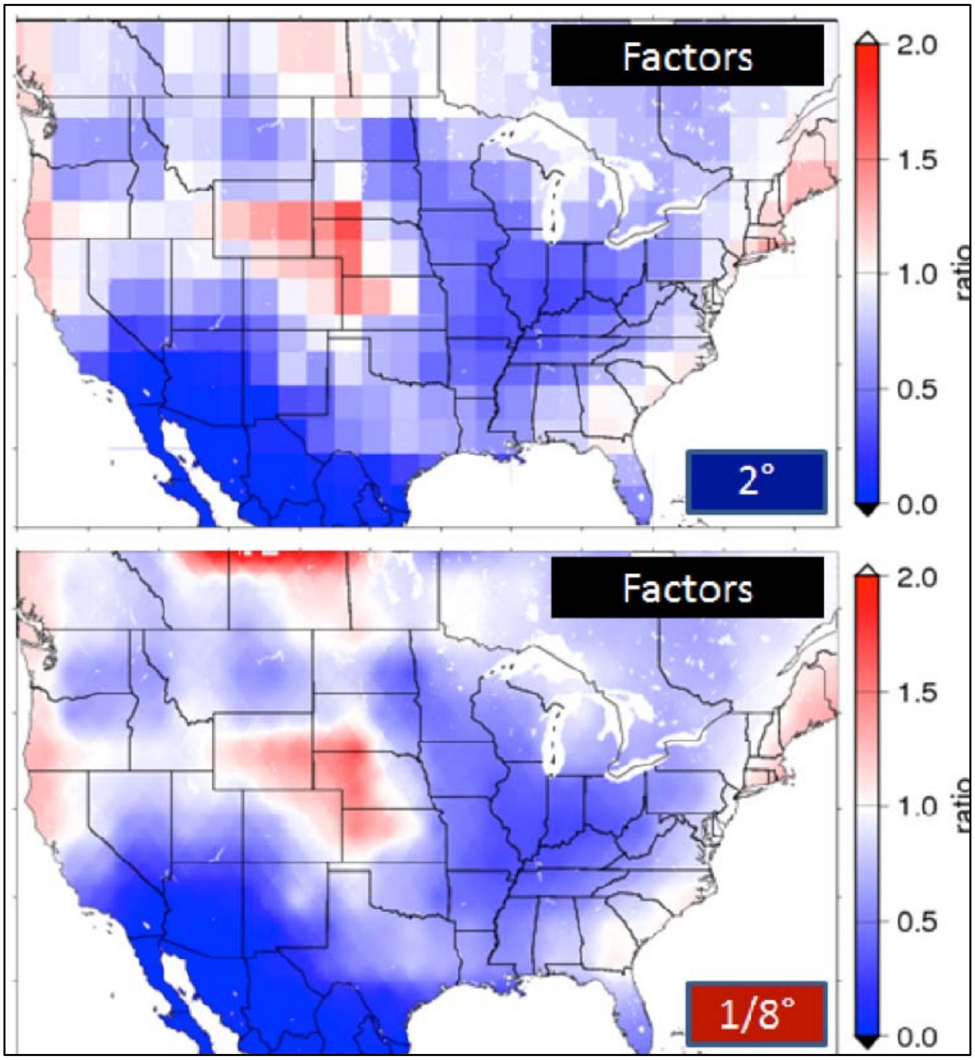

Figure A6. Interpolation of change factors from coarser to finer (downscaled) resolution, continuing with example from figure A5.

1.4 **Computed Downscaled Adjusted GCM:** Merge the downscaled-resolution factor values with the downscaled-resolution OBS spatial climatology to produce downscaled-resolution adjusted GCM values (figure A7). For P change factors, this involves multiplying 1950-1999 mean precipitation at each 1/8° grid cell by the spatially corresponding factor value, thereby obtaining the 1/8° downscaled adjusted GCM values. By multiplying the P factor map (or adding the T factor map) to the original OBS spatial climatology, an observed spatial pattern of monthly climate variability consistent throughout the geographic domain is merged with the adjusted GCM's coarse-resolution spatial change patterns through time to produce the downscaled result.

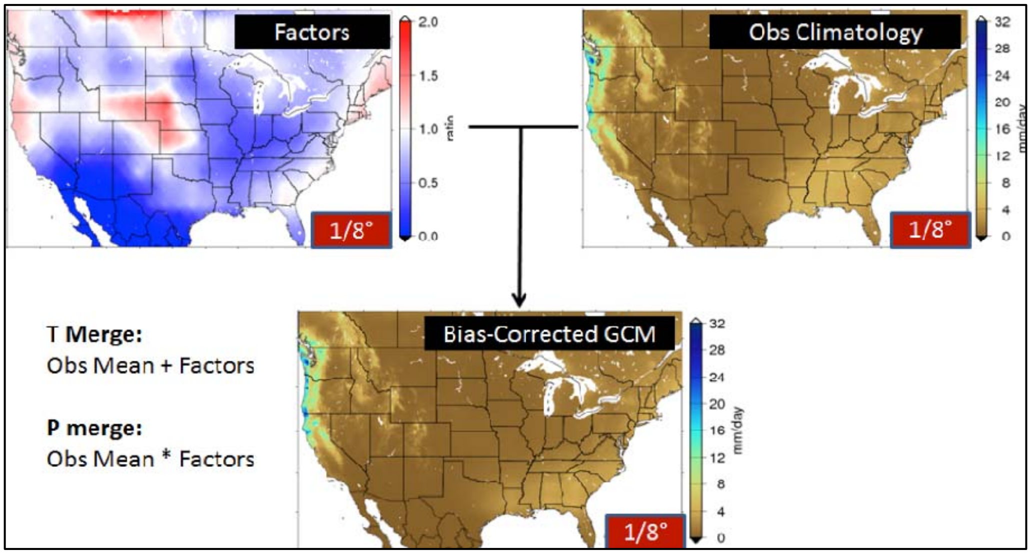

Figure A7. Computation of downscaled values based on downscaled change factors and finer-resolution spatial climatology.

A.2 Daily Bias Correction Constructed Analogs (BCCA)

This procedure was introduced in Hidalgo et al. (2008), Maurer and Hidalgo (2008), and Maurer et al. (2010) and involves the following two-step procedure discussed below. For BCCA CMIP3, the procedure is applied to three periods (or time slices) of GCM output: 1961-2000, 2046-2065, and 2081-2100. For BCCA CMIP5, the procedure is applied to the continuous GCM simulation period of 1950-2099.

BCCA Step 1. Bias-Correction

Similar to the bias-correction featured in "Methodology - BCSD, Step 1," this step identifies how a GCM historical simulation tends to be too wet, dry, cool, and/or warm when compared to observations. The purpose is to identify and remove these tendencies from the projection datasets using a quantile mapping technique similar to that used in monthly BCSD, but with some modification.

- In BCSD, the bias-correction procedure involves generating quantile maps of monthly GCM and OBS values. In BCCA, the quantile maps are constructed from daily GCM and OBS values.

- In BCSD, the bias-correction procedure is applied independently for calendar months. In BCCA, the bias-correction procedure is applied relative to a Julian date, with daily values +/- N days relative to this date being pooled and used to inform the quantile map for that date. In the BCSD CMIP3 and CMIP5 applications, N was set = to 15 days.

- In the BCCA CMIP3 application, the bias-identification period was limited by the duration of simulated historical values rather than OBS values, where the former was simulated 1961-1999. As a result, each day-specific quantile map was informed by (40 years) x (31 values) pairs of simulated and observed values, or roughly 1,240 paired values. In the BCCA CMIP5 application, the bias-identification period did not have the same limitation and was set to 1950-1999 consistent with the BCSD CMIP5 application.

- The BCCA CMIP3 application was applied to global climate projections that had one of three different calendars: 360-day, 365-day with no leap years, and 365-day with leap years (i.e., Gregorian). Prior to bias-correction, projections featuring either of the first two calendars were mapped to a Gregorian calendar. The purpose of this adjustment is to provide a consistent calendar across all projections for the subsetting service ("Projections: Subset Request" tab). To map projections with a 360-day calendar to a Gregorian calendar, the two calendar timelines are first intersected for each year. For each target Gregorian calendar day, data is time-fraction weighted from any intersecting 360-day calendar data. The Gregorian calendar-mapped projection preserves the yearly precipitation volume and temperature averages. Since the procedure does modify the original projection daily sequence somewhat, the original simulation calendar projections were also bias-corrected/downscaled and are available for the entire domain under the "Projections: Complete Archives" tab.[4] The BCCA CMIP5 application was applied to global climate projections that featured one of two different calendars: 365-day with no leap years or Gregorian. Leap days were added to all of the models using a 365-day calendar. This was done by simply averaging February 28 and March 1.

- Daily BCCA CMIP3 application involved applying bias-correction to precipitation, minimum temperature, and maximum temperature. BCCA CMIP5 application involved applying bias-correction to precipitation, maximum temperature, and diurnal temperature range (DTR). Bias-corrected minimum temperature was derived using BC Tmax – BCDTR (Thrasher et al., 2012).

BCCA Step 2. Constructed Analogs

This step spatially translates adjusted GCM projections from REGRID resolution to targeted downscaled resolution. The same observed data used in the BCSD

[4] ftp://gdo-dcp.ucllnl.org/pub/dcp/archive/bcca/.

methodology also inform constructed analogs downscaling. The only difference is that monthly aggregations of these gridded observations are used in BCSD, while daily versions of these gridded observations are used in BCCA.

The procedure is performed on a timestep-specific basis for the full spatial domain. As described on figure A8, it essentially involves identifying a set of day-specific OBS conditions at REGRID resolution that, when combined in a weighted fashion, approximate the adjusted GCM conditions at REGRID resolution for a given day timestep. The weights and dates contributing to this "coarse resolution" analog are then applied with the downscaled-resolution versions of the day-specific OBS conditions, thereby producing the resultant downscaled-resolution analog. See Hidalgo et al. (2008) for more details and examples.

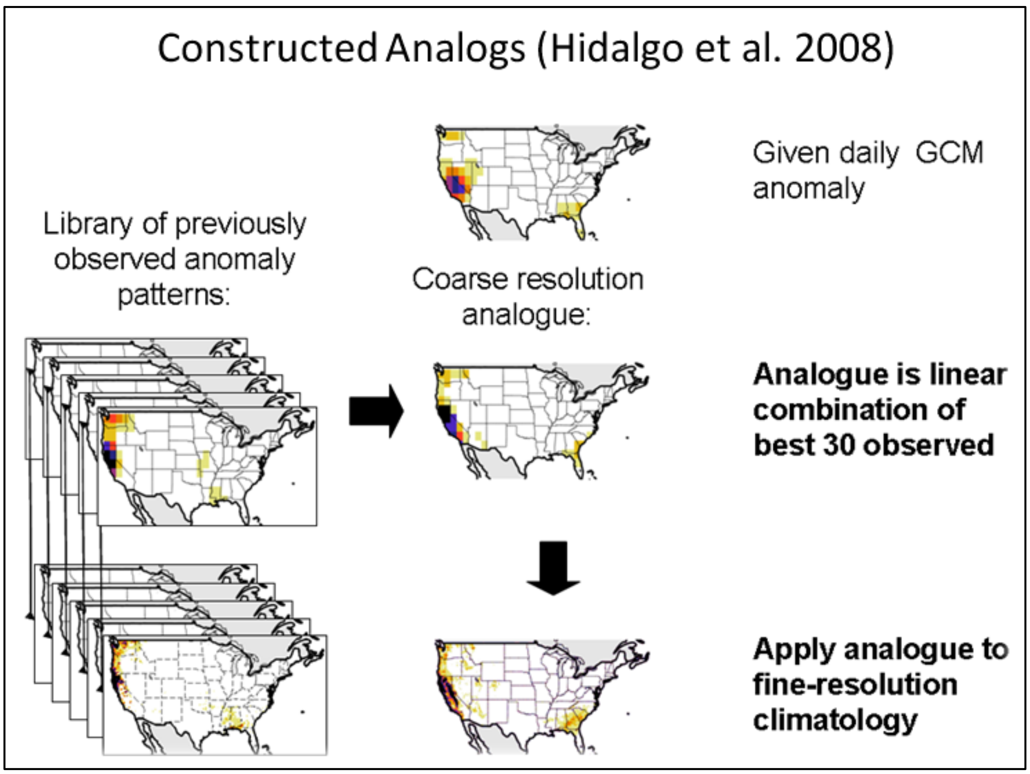

Figure A8. Schematic for identifying a constructed analog of a given day's simulated climate solution.

When constructing an analog for a given timestep, decisions have to be made about:

- How many historical dates (N) are used to construct each daily analog. (For both CMIP3 and CMIP5 applications, N was set to 30 dates.)

- What time-window of (historical) Julian days (D) gets used when searching for historical dates to form the analog of a given GCM date. (For both applications, D was set to 91 days centered on the GCM solution Julian date [i.e., solution date, +/- 45 days].)

- Whether analog construction (i.e., historical date selection) should be coordinated across multiple variables. (For both applications, analog construction was coordinated for daily minimum and maximum temperature. The same N dates were used to construct analogs for these two variables for a given GCM solution date. Analog construction for precipitation on this solution date was free to choose a different set of N historical dates.)

- Whether to construct analogs of magnitude or anomaly patterns; and, if the latter, anomalies relative to what pattern "datum." (For the BCCA CMIP3 application, analogs are constructed relative to 1961-1999 means within the geographic domain of downscaling [i.e., contiguous U.S.], computed separately for each day of year; for BCCA CMIP, the approach is the same, except the historical period is 1950-1999.)

- Whether variables should be transformed prior to analog identification. (For both applications, precipitation was transformed to be square root of precipitation before constructing anomalies and analogs.)

- How to handle instances in CMIP3 application when analog daily minimum temperature (Tmin) at a finer resolution grid cell exceeds the daily maximum temperature (Tmax) (which involved swapping Tmin and Tmax results for situations [projection, grid-cell] where this occurred).

A.3 References

Hidalgo, H. G., M.D. Dettinger, and D.R. Cayan, 2008. *Downscaling with Constructed Analogues: Daily Precipitation and Temperature Fields Over the United States*. California Energy Commission, Public Interest Energy Research Program, Sacramento, California, 62 p.

Maurer E.P., A.W. Wood, J.D. Adam, D.P. Lettenmaier, and B. Nijssen, 2002. "A Long-Term Hydrologically-Based Data Set of Land Surface Fluxes and States for the Conterminous United States," *J. Climate*, 15(22):3237-3251.

Maurer, E.P., 2007. "Uncertainty in Hydrologic Impacts of Climate Change in the Sierra Nevada, California Under Two Emissions Scenarios," *Climatic Change*, 82, 10.1007/s10584-006-9180-9.

Maurer, E.P., and H.G. Hidalgo, 2008. "Utility of Daily vs. Monthly Large-Scale Climate Data: An Intercomparison of Two Statistical Downscaling Methods," *Hydrology and Earth System Sciences*, 12, 551-563, doi:10.5194/hess-12-551-2008.

Maurer, E.P., H.G. Hidalgo, T. Das, M.D. Dettinger, and D.R. Cayan, 2010. "The Utility of Daily Large-Scale Climate Data in the Assessment of Climate Change Impacts on Daily Streamflow in California," *Hydrology and Earth System Sciences,* 14, 1125-1138, doi:10.5194/hess-14-1125-2010.

Pierce, D.W., T. Das, D.R. Cayan, E.P. Maurer, N.L. Miller, Y. Bao, M. Kanamitsu, K. Yoshimura, M.A. Snyder, L.C. Sloan, G. Franco, M. Tyree, 2013. "Probabilistic Estimates of Future changes in California Temperature and Precipitation Using Statistical and Dynamical Downscaling," *Climate Dynamics*, 40, 839-856, doi:10.1007/s00382-012-1337-9.

Reclamation, 2011. *West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Surface Water Projections*. Technical Memorandum No. 86-68210-2011-01, U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Denver, Colorado, 138 p.

Shepard, D.S., 1984. "Computer Mapping: The SYMAP Interpolation Algorithm," *Spatial Statistics and Models*, (G.L. Gaile and C.J. Willmott, eds.), pp. 133-145, D. Reidel, Norwell, Massachusetts.

Thrasher, B.L., E.P. Maurer, C. McKellar, and P.B. Duffy, 2012. "Technical Note: Bias Correcting Climate Model Simulated Daily Temperature Extremes with Quantile Mapping," *Hydrol. Earth Syst. Sci. Discuss*., 9, 5515-5529, doi:10.5194/hessd-9-5515-2012, 2012.

Wood, A.W., E.P. Maurer, A. Kumar, and D.P. Lettenmaier, 2002. "Long-Range Experimental Hydrologic Forecasting for the Eastern United States," *J. Geophysical Research-Atmospheres,* 107(D20), 4429.

Wood, A.W., L.R. Leung, V. Sridhar, and D.P. Lettenmaier 2004. "Hydrologic Implications of Dynamical and Statistical Approaches to Downscaling Climate Model Outputs," *Climatic Change*, 15(62):189-216.

Appendix B

Frequently Asked Questions

Table of Contents

Figures

Appendix B

Frequently Asked Questions

B.1 What other downscaling methodologies might have been used?

For the purposes of this archive, "downscaling" is the process of taking native-scale global climate model (GCM) results of global climate responses to changing global atmospheric composition and postprocessing those through additional statistical or dynamical models to create a set of results at finer spatial scale that is more meaningful in the context of local and regional impacts. The many methods for achieving this are extensively discussed in many reports, especially the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment (Christensen et al., 2007, Chapter 11: Regional Climate Projections) and other summaries (Wigley, 2004).

Two general approaches are used in downscaling:

- Dynamical, where a finer scale regional climate model (RCM) with a better representation of local terrain simulates climate processes over the region of interest

- Nondynamical (e.g., statistical, empirical, simple) downscaling where large-scale climate features are statistically or empirically related to fine-scale climate for the region.

For simulating current climate, the two methods have been shown to be generally comparable (Maurer and Hidalgo, 2008; Maurer et al. 2010). There have been numerous efforts to perform dynamical downscaling using different RCMs, including those coordinated under the North American Regional Climate Change Assessment Program (NARCCAP). A key challenge with any dynamical downscaling approach is the computational requirement of RCM implementation, which tends to challenge the feasibility of an effort featuring many projections and multiple future decades.

When considering a nondynamical approach for developing an archive of this nature, the selected nondynamical method should have the following characteristics:

- Well tested and documented, especially in applications in the U.S.

- Automated and efficient, to downscale 100 to 200 projections of monthly conditions from multiple GCM variables in a reasonable timeframe.
- Able to produce output that statistically matches observations for a historical period (i.e., features a bias-correction scheme).
- Capable of producing spatially continuous, fine-scale gridded output of precipitation and temperature suitable for water resources and other watershed-scale impacts analysis (i.e., downscales to a satisfactory resolution to support such impacts analyses).

At the time of original archive development in 2007, various nondynamical techniques were surveyed; only monthly bias-correction and spatial disaggregation (BCSD) was found to meet all of these criteria. By 2010, the daily bias-correction and constructed analogs (BCCA) technique had arrived, also meeting these criteria. As a result, it was selected to support daily downscaled Coupled Model Intercomparison Project phase 3 (CMIP3) projections added to the archive in 2011. Since then, other techniques have emerged, including daily BCSD (Abatzaglou and Brown, 2011), daily asynchronous regression (Dettinger et al., 2004; Stoner et al., 2012; supporting related daily CMIP3 downscaling supported by the U.S. Geological Survey National Climate Change and Wildlife Science Center), and daily Multivariate Adapted Constructed Analogs technique (Abatzaglou and Brown, 2011; a close sibling of BCCA with several features well-tailored for assessing evolving wildfire risk under climate change). Understanding the relative merits of these emergent techniques relative to monthly BCSD and daily BCCA remains a matter of research.

B.2 How does the BCSD methodology contrast from other methods, and what are its relative strengths and weaknesses relative to other methods?

Dynamical downscaling features an RCM nested within a GCM domain and at a finer spatial scale, with the goal of representing local climate response to the changing global climate. While the RCM is nested within and forced by a GCM at its boundaries, it can simulate local fine-scale feedback processes not anticipated with statistical methods. RCMs are computationally intensive and are thus typically applied against a few future GCM projections and for time slices of a few decades. RCMs could not be reasonably applied to the large CMIP3 and monthly Coupled Model Intercomparison Project phase 5 (CMIP5) ensembles described in table 1 and table 2 of the main report.

One class of nondynamical downscaling involves identifying explicit statistical transfer functions. This class is typically used to predict one variable at one site, though some "statistical" techniques have been developed for simultaneous downscaling to multiple sites for precipitation (Harpham and Wilby, 2005; Wilks, 1999). However, for studies of impacts to watershed hydrology or other regional natural systems, it is important to simultaneously downscale values of multiple variables (such as precipitation and temperature) over large, heterogeneous areas, while maintaining physically plausible spatial and temporal relationships. Few downscaling techniques have been developed to do this. At the time of original archive development in 2007, the monthly BCSD technique was unique in that it could produce gridded time series of monthly precipitation and surface air temperature at a fine resolution over a large spatial domain. The BCSD method has also been shown to provide downscaling capabilities comparable to other statistical and dynamical methods in the context of hydrologic impacts (Wood et al., 2004).

Since 2007, the daily BCCA and MACA techniques have emerged, both in the class of analog-based, nondynamical downscaling. Maurer et al. (2010) offer a comparison of BCCA and BCSD projections, showing that the two methodologies produce monthly climate projection information having similar strengths and weaknesses. Abatzoglou and Brown (2011) offer a similar comparison of MACA and BCSD, suggesting similar findings. Both studies tout strengths of analog-based downscaling over the spatial disaggregation approach of BCSD if the interest is on studying downscaled projected daily conditions that correspond to the daily sequences simulated by the underpinning GCMs. Note that monthly BCSD projections have frequently been used to inform daily hydrologic analysis (Christensen et al. 2004; Hayhoe et al., 2004; Hayhoe et al., 2007; Maurer and Duffy, 2005; Maurer, 2007; Payne et al., 2004; Van Rheenen et al., 2004; Wood et al., 2004; Reclamation 2011), but only by implementing a time-disaggregation procedure that maps monthly BCSD climate projections to daily hydrologic model forcings and essentially involves resampling and scaling observed daily conditions to conform to monthly BCSD projections (Wood et al., 2004).

The principal weakness of any nondynamical downscaling method is the assumption of some temporal stationarity in the relationship between large-scale climate features and local scale surface climate. For example, in the case of BCSD, the assumption of spatial disaggregation is that the processes determining how precipitation and temperature anomalies for any 2 degree (º) grid box are distributed to 1/8º within that grid box will be the same in the future as they have been in the past. Also, in the case of BCSD, the bias-correction step features the assumption that any biases exhibited by a GCM for the historical period will be exhibited in future simulations. Tests of these assumptions, using historic data, show that they appear to be reasonable, inasmuch as the BCSD method compares favorably to other downscaling methods (Wood et al., 2004). BCCA features similar limiting assumptions.

B.3 How do BCSD and BCCA compare with one another?

The BCSD and BCCA methodologies begin with a similar bias correction step (appendix A). For monthly BCSD, bias correction is done at a monthly level; for daily BCCA, it is applied to each Julian day informed by simulated and observed daily conditions for a period of days before and after the target Julian day.
The BCSD and BCCA spatial downscaling steps differ more substantially. BCSD downscaling is applied on a time-step basis and consists of representing the coarse-resolution, bias-corrected simulated conditions of a given variable as a spatial-change anomaly relative to a coarse-resolution spatial "datum" (i.e., a reference historical spatial climatology), disaggregating the coarse-resolution change anomalies to finer resolution, and then merging the finer-resolution change anomalies with the finer-resolution "datum" to compute a downscaled version of the timestep conditions. An example illustration of coarse-resolution to finer resolution change anomalies is shown on figure B1. If the resultant monthly downscaled conditions need to be temporally disaggregated to daily values, this can be done using the technique described in Wood et al. (2004), which essentially involves historical month sampling and scaling.

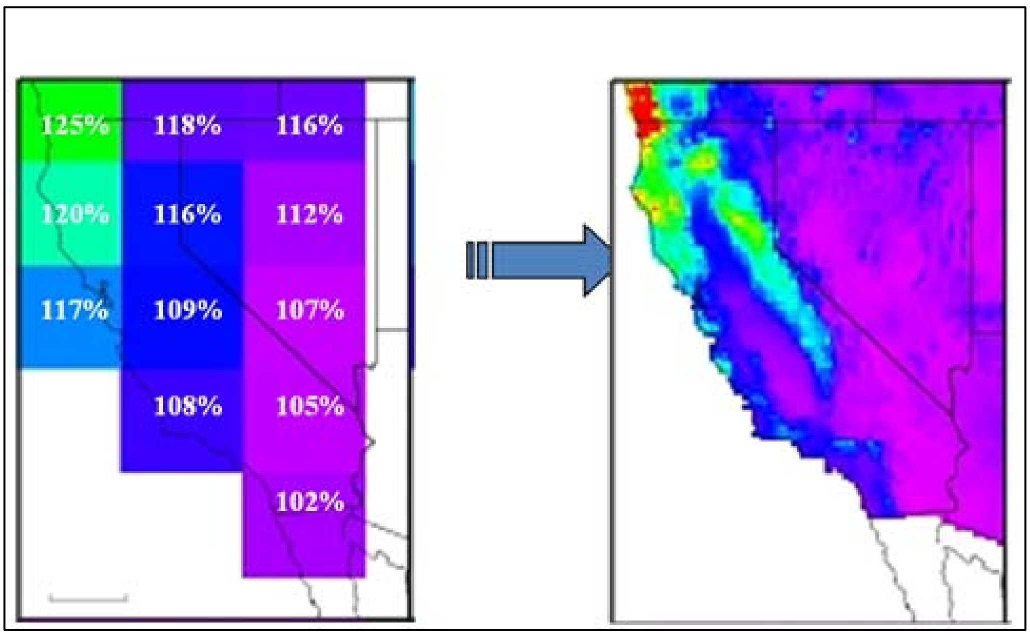

Figure B1. Interpolation of large-scale anomalies to fine grid.

BCCA spatial downscaling is also applied on a timestep basis, but it proceeds on daily timesteps rather than monthly timesteps. It consists of constructing an observations-based analog of the climate model's simulated condition. The first step involves assembling a library of observed daily coarse-resolution and corresponding finer resolution observed climate anomaly patterns of the variable to be downscaled. Then, for a given Julian date of climate simulation output, a subperiod of the library is considered for offering candidate, observed climate anomaly patterns (i.e., +/- 30 days in this BCCA application, as explained in appendix A). To downscale each day, a subset of 30 observed candidate anomaly patterns (predictors) is selected where members have the closest similarity to the simulated anomaly of the target Julian date. A linear combination of the 30 observed candidate anomaly patterns is then fit with the 30 fitting parameters estimated to minimize spatial error with the simulated anomaly. This linear combination is the coarse-resolution version of the constructed analogue. The finer resolution, or downscaled, version is computed by using the same maps and observed anomaly dates, but with application using the finer-resolution observed climate anomaly patterns from those dates. These downscaling steps are illustrated on figure B2.

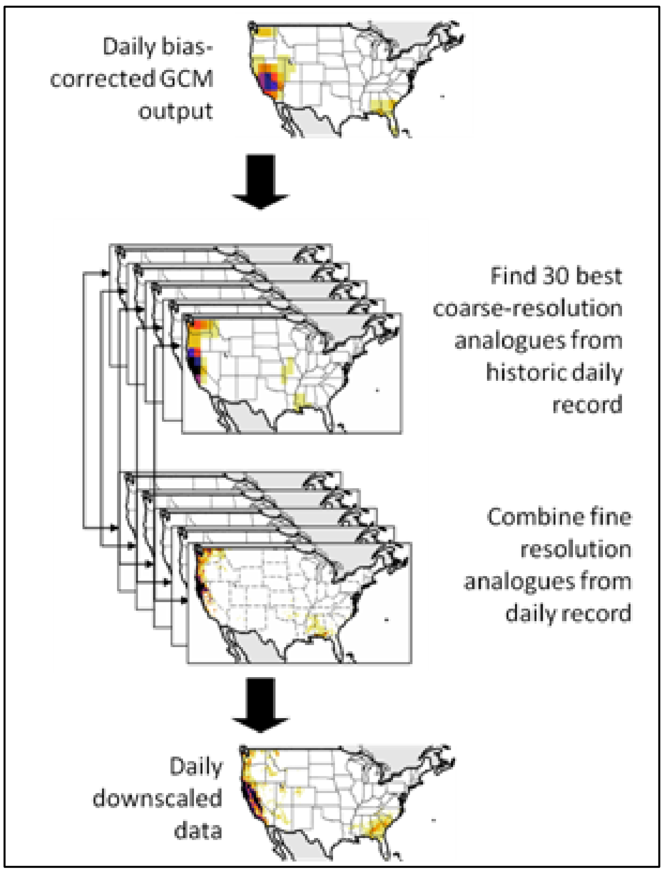

Figure B2. Spatial downscaling step of BCCA.

Maurer et al. (2010) offer a comparison of projected conditions stemming from BCCA and BCSD, which factors in the joint influences of bias-correction and spatial downscaling differences between the methodologies. In this comparison, the monthly BCSD results have been temporally disaggregated to daily, following Wood et al. (2004), setting up more direct comparison to daily BCCA conditions. The most important distinction between the two methods, when considering daily statistics, is that using daily output BCCA retains the daily sequencing of weather events from the coarse resolution, while in BCSD, only monthly averages are used. Where a climate model exhibits skill in simulating daily variability, BCCA would, in theory, be capable of capturing that skill, while BCSD would reflect historical intramonth variability. Thus, for daily statistics, the two methods will be expected to distinguish themselves only inasmuch as the large-scale climate model exhibits skill at the daily time scale. Another distinction between BCSD and BCCA has been observed in areas near coasts and other areas with sharp climate gradients at a scale much finer than the large-scale climate model output being downscaled. While BCSD reproduces climatological patterns of precipitation and temperature, projected changes tend to be smooth spatially. BCCA, by contrast, captures changes in day-to-day variability, which can evolve differently than the large-scale forcing; thus, BCCA can produce sharper spatial gradients of precipitation and temperature changes than BCSD.

Another way to view the spatial downscaling methodologies of BCSD and BCCA is to recognize that the philosophy of daily BCCA downscaling is to go after a daily to submonthly set of simulated climate changes that are disregarded by monthly BCSD downscaling. Where monthly BCSD cannot capture submonthly phenomena that may (or may not) rightly show up in the GCMs under future forcings (e.g., systematic changes in the frequency of numbers of wet versus dry days within a month, or the frequency of sharp cold snaps or heat waves), daily BCCA is specifically geared to do so. One thing that neither BCCA nor BCSD will do well at is capturing a regional circumstance where an entirely new set of processes creeps into the region. For example, if spring-summer monsoon weather reaches new areas of the Southwester U.S. under climate change, both BCCA and BCSD would be challenged to use historical weather patterns uninfluenced by historical monsoon conditions to reproduce the finer spatial structure of these future monsoon-influenced weather patterns.

B.4 What are some planning applications that might be supported by monthly BCSD and daily BCCA climate projections?

The climate projections of this archive could be used to address several types of planning questions, ranging from projections survey to impacts analysis. Some examples include:

- Exploring the consensus among contemporary projections over a “local region” (e.g., Payette River basin in Idaho).

- Exploring how local projection consensus compares to distributed consensus in a larger region (e.g., Payette River basin within the larger Pacific Northwest region).

- Exploring what time series projection information implies for climate-dependent resources in a local region, in relation to a specific planning question, region, and look-ahead horizon (e.g., water, energy, ecosystem services in the Payette River basin, roughly by mid-21st century).

Daily BCCA information can be applied to explore the same interests, but with the added expense of working with daily data rather than monthly data. However, daily BCCA information also supports other assessments not well supported by monthly BCSD. Some examples include:

- Assessing projected changes in the variability of daily to multiday precipitation events that may be relevant to flood control or other systems that are sensitive to daily precipitation variability.

- Assessing projected changes in diurnal temperature range and multiday temperature extremes, which may be relevant to vulnerability assessments concerning terrestrial and aquatic ecosystems.

B.5 What are some uncertainties associated with using BCSD and BCCA climate projections, and how might the level of confidence in projection use vary by application?

As stated in the preceding discussion, these archive projections could conceivably be used to support statements of projection consensus, possibly through analysis of climate change "projection density functions" (Brekke et al., 2008). One could apply such density functions to inform judgments of projection consensus within the ensemble being surveyed. Although there may be an inclination to use the density functions to guide statements on "climate change probability," such application should be avoided. One reason is that key climate change uncertainties are not represented within the spectrum of available climate projections, whether we are focusing on CMIP3 or CMIP5. Another reason is that there are uncertainties associated with bias-correction and spatial downscaling, leading to multiple proposed methodologies (discussed under question 2).

To illustrate, the information in the BCSD CMIP3 climate projections archive represents a heterogenous mix of 16 CMIP3 GCMs that were used to simulate three emissions pathways, given one or more initial conditions (runs) per model emissions combination. The models reflect various states of modeling capability and a crude cross section of the uncertainties concerning future emissions. Not represented among these projections are the uncertainties associated with the many factors not included in current climate models or in the pathways considered here (e.g., assumed global technological development, distributed energy-technology portfolios, resultant spatial distribution of greenhouse gas (GHG) sources and sinks through times, biogeochemical interaction with GHG sources and sinks, and many others). The situation of representing key climate and social process without being able to exhaustively represent uncertainties is still evident in CMIP5. For these reasons, it is important to interpret any “climate projection density” functions produced from these projections as being a characteristic of the ensemble considered and not the full range of uncertainties (Mote et al., 2011). In the end, “climate projection densities” are expected to be distinctly different from climate-change probabilities.

Application uncertainties vary, depending on which spatial and temporal aspects of climate projections are used, regardless of whether the application involves only climate projections evaluation or that as well as subsequent impacts assessment (Mote et al., 2011). Arguably, statistical descriptions of these projections (e.g., period and spatial statistics) are more reliable than location- or timestep-specific conditions. For example, these projections can be used more confidently to support statements on projected changes in mean annual temperature over a given region (e.g., during a 2041-70 future period relative to a 1971-2000 base period) than to describe a specific future month's condition in that region (e.g., during January 2061). Also, applications involving only a projections survey have arguably less uncertainty than those involving projections survey as well as subsequent impacts modeling because the latter introduces uncertainties associated with impacts modeling and analysis.

For applications involving impacts assessments, it may be worthwhile to know that many users have applied archive projections to construct climate change scenarios from historical to future periods, which subsequently inform a “Period-Change” impacts assessment where impacts are measured between evaluating the resource under historical weather and climate change-adjusted weather conditions (e.g., Miller et al., 2003). Other users have translated the ensemble of the climate projections into resource projections, thereby producing a time-evolving or “Transient” view of resource conditions from past to future (e.g., Maurer 2007). Use of the latter approach implies placing relatively more confidence in the transient and evolving aspects of climate projections (e.g., phases of climate oscillations that vary on interannual to interdecadal time scales). When applied with the monthly BCSD projections, the transient approach involves placing confidence in evolving monthly aspects of climate; when applied with daily

BCCA, the confidence telescopes to evolving daily aspects of climate. At this point in time, there is no guidance on whether a Period-Change or Transient method is more appropriate for impacts assessment. Preference for one class of method often stems from practicalities of implementing one class versus the other.

B.6 References

Abatzoglou, J.T., and T.J. Brown, 2011. "A Comparison of Statistical Downscaling Methods Suited for Wildfire Applications," *International Journal of Climatology,* doi: 10.1002/joc.2312.

Brekke, L.D., M.D. Dettinger, E.P. Maurer, and M. Anderson, 2008. "Significance of Model Credibility in Estimating Climate Projection Distributions for Regional Hydroclimatological Risk Assessments," *Climatic Change*, Vol. 89, No. 3-4, 371-394, doi: 10.1007/s10584-007-9388-3.

Christensen, J.H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.T. Kwon, R. Laprise, R., V. Magaña Rueda, L. Mearns, C.G. Menêndez, J. Räisänen, A. Rinke, A. Sarr, and P. Whetton, 2007. "Regional Climate Projections," *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.), Cambridge University Press, Cambridge, United Kingdom and New York, New York, USA.

Christensen, N. S., Wood, A. W., Voisin, N., Lettenmaier, D. P., and Palmer, R.N., 2004. "The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin," *Climatic Change*, 62, 337-363.

Dettinger, M.D., D.R. Cayan, M.K. Meyer, and A.E. Jeton, 2004. "Simulated Hydrologic Responses to Climate Variations and Change in the Merced, Carson, and American River Basins, Sierra Nevada, California, 1900–2099," *Climatic Change*, 62, 283–317.

Harpham, C., and Wilby, R. L., 2005. "Multi-Site Downscaling of Heavy Daily Precipitation Occurrence and Amounts," *J. Hydrol*., 312, 235-255.

Hayhoe, K., D. Cayan, C.B. Field, P.C. Frumhoff, E.P. Maurer, N.L. Miller, S.C. Moser, S.H. Schneider, K.N. Cahill, E.E. Cleland, L. Dale, R. Drapek, R.M. Hanemann, L.S. Kalkstein, J. Lenihan, C.K. Lunch, R.P. Neilson, S.C. Sheridan, and J.H. Verville, 2004. "Emissions Pathways, Climate Change, and Impacts on California," *Proc. National Academy Sci.*, 101, 12422-12427.

Hayhoe, K., C.P. Wake, T.G. Huntington, L. Luo, M.D. Schwartz, J. Sheffield, E. Wood, B. Anderson, J. Bradbury, A. Degaetano, T.J. Troy, D. Wolfe, 2007. "Past and Future Changes in Climate and Hydrological Indicators in the U.S. Northeast," *Climate Dynamics*, 28 (4): 381-407.

Hidalgo, H.G., M.D. Dettinger, and D.R. Cayan, 2008. *Downscaling with Constructed Analogues: Daily Precipitation and Temperature Fields Over the United States.* California Energy Commission, Public Interest Energy Research Program, Sacramento, California, 62 p.

Maurer, E.P., A.W. Wood, J.D. Adam, D.P. Lettenmaier, and B. Nijssen, 2002. "A Long-Term Hydrologically-Based Data Set of Land Surface Fluxes and states for the conterminous United States. *J Climate* 15(22):3237-3251.

Maurer, E. P., and Duffy, P. B., 2005. "Uncertainty in Projections of Streamflow Changes Due to Climate Change in California," *Geophys. Res. Lett.,* 32, doi:10.1029/2004GL021462.

Maurer, E.P., 2007. "Uncertainty in Hydrologic Impacts of Climate Change in the Sierra Nevada, California Under Two Emissions Scenarios," *Climatic Change*, 82, 10.1007/s10584-006-9180-9.

Maurer, E.P., and H.G. Hidalgo, 2008. "Utility of Daily vs. Monthly Large-Scale Climate Data: An Intercomparison of Two Statistical Downscaling Methods," *Hydrology and Earth System Sciences*, 12, 551-563, doi:10.5194/hess-12-551-2008.

Maurer, E.P., H.G. Hidalgo, T. Das, M.D. Dettinger, and D.R. Cayan, 2010. "The Utility of Daily Large-Scale Climate Data in the Assessment of Climate Change Impacts on Daily Streamflow in California," *Hydrology and Earth System Sciences,* 14, 1125-1138, doi:10.5194/hess-14-1125-2010.

Miller, N.L., K. Bashford, and E. Strem, 2003. "Potential Climate Change Impacts on California Hydrology," *Journal of the American Water Resources Association*, 39, 771-784.

Mote, P., L. Brekke, P.B. Duffy, and E. Maurer, 2011. "Guidelines for Constructing Climate Scenarios," *Eos Transactions*, 92(31), 257-258.

Payne, J.T., A.W. Wood, A.F. Hamlet, R.N. Palmer, and D.P. Lettenmaier, 2004. "Mitigating the Effects of Climate Change on the Water Resources of the Columbia River Basin," *Climatic Change*, 62, 233-256.

Pierce, D.W., T. Das, D.R. Cayan, E.P. Maurer, N.L. Miller, Y. Bao, M. Kanamitsu, K. Yoshimura, M.A. Snyder, L.C. Sloan, G. Franco, and M. Tyree, 2013. "Probabilistic Estimates of Future Changes in California Temperature and Precipitation Using Statistical and Dynamical Downscaling," *Climate Dynamics*, 40, 839-856, doi:10.1007/s00382-012-1337-9.

Reclamation, 2011. *West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Surface Water Projections*. Technical Memorandum No. 86-68210-2011-01, prepared by the U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Denver, Colorado, 138 p.

Shepard, D.S. 1984. Computer Mapping: "The SYMAP Interpolation Algorithm," *Spatial Statistics and Models*. G.L. Gaile and C.J. Willmott (eds.), p. 133 145, D. Reidel, Norwell, Massachusetts.

Stoner, A., K. Hayhoe, and X. Yang, 2012. "An Asynchronous Regional Regression Model for Statistical Downscaling of Daily Climate Variables," *International Journal of Climatology*, doi:10.1002/joc.3603.

Van Rheenen, N.T., A.W. Wood, R.N. Palmer, and D.P. Lettenmaier, 2004. "Potential Implications of PCM Climate Change Scenarios for Sacramento-San Joaquin River Basin Hydrology and Water Resources," *Climatic Change*, 62, 257-281.

Wigley, T.M.L., 2004. "Input Needs for Downscaling of Climate Data." Discussion paper prepared for California Energy Commission Public Interest Energy Research Program, Rep 500-04-027.

Wilks, D. S., 1999. "Multisite Downscaling of Daily Precipitation with a Stochastic Weather Generator," *Clim. Res.*, 11, 125-136.

Wood, A.W., E.P. Maurer, A. Kumar, and D.P. Lettenmaier, 2002. "Long-Range Experimental Hydrologic Forecasting for the Eastern United States," *J. Geophysical Research-Atmospheres,* 107(D20), 4429.

Wood, A.W., L.R. Leung, V. Sridhar, and D.P. Lettenmaier, 2004. "Hydrologic Implications of Dynamical and Statistical Approaches to Downscaling Climate Model Outputs," *Climatic Change*, 15(62):189-216.

Appendix C

Section 3.2 Graphics for Additional Case Study Basins

Appendix C

Section 3.2 Graphics for Additional Case Study Basins

Section 3.2 of the main report addresses questions about how basin-integrated climate changes from monthly bias-correction and spatial disaggregation (BCSD) versions of results from Coupled Model Inter-comparison Project phase 3 (CMIP3) and phase 5 (CMIP5) compare and contrast. Section 3.2 refers to these results as BCSD3 and BCSD5, respectively. A basin-integrated evaluation informs how spatially distributed differences in BCSD5 and BCSD3 changes integrate to portray difference over a region of interest, which may be more relevant for user purposes. Section 3.2 provides graphical illustrations of basin-integrated change over the Upper Colorado Basin, as well as discussion on how to interpret these graphical results with respect to the following questions:

- How are the climate change distributions similar and different by the mid-21st century?
- Does climate model balancing affect impressions about distribution differences?
- Do the two steps of BCSD affect impressions?
- Does separation of results by emissions scenario affect impressions?
- How are the central-tendency monthly climate changes similar and different by the mid-21st century?

This appendix provides graphical results for additional case study basins, but it leaves the exercise of interpreting and summarizing results to the reader. Additional case study basins include:

- Klamath River near the California/Oregon border
- Missouri River near Milk River confluence, Montana
- North Fork Platte River near Lake McConaughy, Nebraska
- South Fork Platte River near Lake McConaughy, Nebraska
- Rio Grande at Elephant Butte Dam, New Mexico
- Sacramento River near Freeport, California
- San Joaquin River near Vernalis and below Mendota Pool, California
- Snake River at Brownlee, Idaho
- Truckee River at Nixon, Nevada

Graphics are included in the compressed archive located at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/downscaled_climate_AppendixC_Figures.zip. Graphic file names are <basin><figure number>.bmp, where "figure number" corresponds to the figure number in section 3.2 (i.e., figures 8 through 14).